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STUDY OF THE INTERACTIONS BETWEEN THE DIFFERENT WIND COMPONENTS IN THE UPPER ATMOSPHERE

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STUDY OF THE INTERACTIONS BETWEEN THE DIFFERENT WIND COMPONENTS IN THE UPPER ATMOSPHERE[1]

A. Spizzichino[2]

ABSTRACT. It has been generally accepted until now that winds in the mesosphere and lower thermosphere result from the superposition of components - prevailing wind, tides gravity waves - which do not interact.

The meteor trails observations made in Garchy clearly confirm the existence of these components, but suggest that they are strongly interacting. A theoretical study of non-linear effects confirms the importance of these interactions; it shows in particular that the diurnal tide yields energy to gravity waves propagating through the mesosphere: such a mechanism provides an explanation for many observed properties of tides and gravity waves. This theory of non-linear effects can be applied to other phenomena occuring in the higher atmosphere.

Introduction

The knowledge of motion in the upper atmosphere (i.e. above thirty kilometers) is essential in order to understand the system of physicochemical phenomena of which it is the seat. As a matter of fact, we still have available only very incomplete data concerning this motion - the winds - which are based practically entirely on the observations carried out during the last fifteen years. These involve the detection of meteor trails and irregularities of ionization which have allowed systematic measurements of winds between 80 and 110 km in altitude. Experiments making use of rockets have supplied some wind profiles between 30 and 60 km (aerological rockets) and between 90 and 160 km (ejection of luminescent clouds). /2

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1. Only part I of this study appears in this issue of the Annales de Geophysique. Parts II and III will appear in Volume 25, No. 4, 1969. Parts I and V will appear in 1970.

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*Numbers in the margin indicate pagination in the foreign text.

A method for analyzing upper atmosphere winds was slowly developed from these measurements. These winds result from the superposition of a permanent motion called the dominant wind and oscillatory motions: the diurnal tide, with a 24 hour period, the semidiurnal tide, with a 12 hour period, and gravity waves which have a shorter period (several hours)[3].

Two sorts of reasons led to this analysis of winds using four components. Some reasons were experimental in origin. Some of these components (prevailing wind, semidiurnal tide) appear clearly in the winds observed and it was possible to ascertain the permanency of their properties in the passage of time (from one year to another) and in space (from one position to another).

Other reasons were theoretical in origin. It can be shown that low amplitude motions can be depicted by linear equations whose solution is produced by superposing a constant wind and wavy motions. These different components should be independent from each other, i.e., each one of them should be propagated as if the others did not exist. This last property shows that the separation of winds into components is not just a convenient way of classifying experimental observations. It allows, on the contrary, the separation of distinct physical phenomena.

This breakdown of the winds into independent components is the basis for the quasi-totality of studies so far published. This is, to a great extent, the reason why it will be addressed in the present work.

For this reason, we shall first of all examine some experimental results, more particularly those recently obtained using the meteor radar installed by the CNET at Garchy.[4] The observations made previous to those made at Garchy did not allow direct observation of the propagation of gravity waves and the

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3. The term wind has been used by us to designate the system of motions with a scale greater than one kilometer. This, therefore, excludes the small-scale turbulence which will not be discussed here. All the slight variations of the wind (annual, or even with a several-day period) are included in the prevailing wind.

4. The observations made at Garchy enjoyed the financial support of the National Center for Space Studies (CNES) and the AISC.

very irregular diurnal tide appeared to refuse to obey any law. The measurements made at Garchy clearly confirmed the existence of gravity waves [Revah, 1969] and we shall see that the irregular structure of the diurnal tide can be explained by the presence of several oscillations of neighboring periods. The analysis of winds into wavy components therefore appears to be justified.

Since this time, the results produced at Garchy allowed specification of several properties of tides and gravity waves. These properties suggest that, although the separation of winds into components is valid as a first approximation, these components are far from being independent and taking place between them should be large energy exchanges, chiefly above 70 km in altitude.

In order to study these phenomena in more detail, we were obliged to develop a theory of interactions between atmospheric waves. This theory shows more particularly that the diurnal tide yields a great part of its energy to gravity waves above 70 km in altitude. These waves are amplified in this way at the expense of an energy coming from the solar heating of the atmosphere. We shall see that this phenomenon allows explanation of most of the characteristics of the gravity waves observed at Garchy.

Although a great part of this work is devoted to this interaction between diurnal tide and gravity waves, its scope is more general.

Thus, all the studies thus far carried out on gravity waves and tides are based on oversimplified diagrams whose revision is advisable. It is assumed, for example, that a short-period wave (gravity wave) can only receive its energy from a short-period source - which more often than not should be located at a very low altitude - and that it subsequently can only be propagated to a height at which it is either dissipated or reflected. The special example of the interactions between tides and gravity waves shows that a wave can receive energy from a source with a different period, or, on the contrary, yield energy and progressively fade away.

The existence of such interactions above 70 km in altitude is not limited to the diurnal tide and to gravity waves. It concerns all components of the wind. We shall see, for example, that interactions between tides can give rise simultaneously to a prevailing wind, harmonics, different modes of oscillation, all of which can perceptibly modify the morphology of the very high altitude atmospheric winds. Furthermore, these energy exchanges can lead to the formation of oscillations with shorter and shorter wavelengths starting off the turbulent degeneration of the winds. /3

We shall begin this study by an examination of the properties of tides and gravity waves which have been observed experimentally, more particularly using the Garchy meteor radar. We shall provide a short explanation, from an intuitive viewpoint, why these properties suggest the existence of powerful interactions between the different wind components (Part I).

Part II will be devoted to a short summary of the theory of atmospheric waves. In this part, we have attempted to simultaneously cover tides and gravity waves in a report much more synthetic in nature than those previously published. We shall in this way be better prepared to deal with the theoretical study of interactions between atmospheric waves covered in Part III.

In Part IV we shall apply the results of this study to the interactions between gravity waves and the diurnal tide in the lower thermosphere. The conclusions arrived at will be compared with the experimental results provided in Part II.

Finally, Part V will be devoted to a quick listing of the other possible applications of the theory of non-linear interactions between atmospheric waves.

EXPERIMENTAL STUDY OF WINDS IN THE UPPER ATMOSPHERE

A. Spizzichino

Part I

ABSTRACT. The experimental results obtained at Garchy from meteor observation are examined, and compared with other experiments. The semi-diurnal tide is found to be a rather regular oscillation, with properties nearly similar to those of the S_2^2 theoretical mode. On the contrary, the diurnal tide is very irregular; its phase variations are so important, that its instantaneous frequency varies between 17 and 35 hr. (many difficulties of experimentalists can so be explained). Some intuitive comments suggest that the differences between the properties of the two tides possibly result from interactions between the tides and the other components of the wind. Such interactions can also provide an explanation for the observation, at Garchy, of gravity waves having the same vertical wavelength as the diurnal tide.

I. Introduction

This part will be devoted to an examination of what we have learned experimentally concerning winds in the upper atmosphere. This study will involve the system of winds between 30 and 150 km in altitude. Furthermore, we shall be more particularly interested in the region included between 80 and 110 km, in which measurements were made more often and where we have available unpublished data supplied by the meteor radar of the CNET at Garchy. /5

The meteor radar installed in France at Garchy (47°N, 3°E) is bistatic, operates at 29.9 MHz and, in its present form[5], only measures the east-west wind component. Its detailed description can be found in several previous

5. A second meteor radar presently being installed will provide the north-south wind component beginning from 1970.

publications [Spizzichino et al., 1965; Revah, 1969].

The advantages of this radar in relation to previous designs are chiefly:

its sensitivity, allowing detection of a great number of meteor echos (approximately 1,500 daily) which should, in principle[6], provide just as many wind measurements,

its precision: the altitude of each echo is, in principle[6], defined to approximately ± 0.5 km.

Owing to both these advantages, the Garchy radar allowed the complete reconstruction of the profile of winds around 90 km in altitude. An example of this can be seen with Figure 1 which provides the profile of winds produced during a recording run lasting 48 hours (13 - 15 September 1966).

We shall use in this chapter the results of ten observation runs of the Garchy meteor radar, made over a one-year period (September 1965 - September 1966). Each one of these runs lasted from 48 to 72 hours without interruption: their exact dates are provided as an annex.

We shall compare these results with those obtained by other experimenters and will try to avoid reducing this chapter to a catalog of the characteristics of winds observed at Garchy. We shall rather attempt to present a synthesis of these new data and previous works.

We shall not attempt to undertake an exhaustive study of all properties of the winds. In reality:

(1) We shall limit ourselves to study of the variable components of the wind (i.e. excluding the prevailing wind). The semidiurnal tide will be studied in paragraph 3, the diurnal tide in paragraph 4. The gravity waves discussed in detail in [Revah, 1969] will form the subject of a briefer examination in paragraph 5.

(2) We shall not consider the establishment of a catalog of properties

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6. Since the observations described below were carried out during a period of development, precision in altitude was, on the average, only ± km, and only 40 to 50% of the 1,500 echoes received supplied a wind measurement.

Zonal wind
Garchy 13 - 15 Sept. 1966

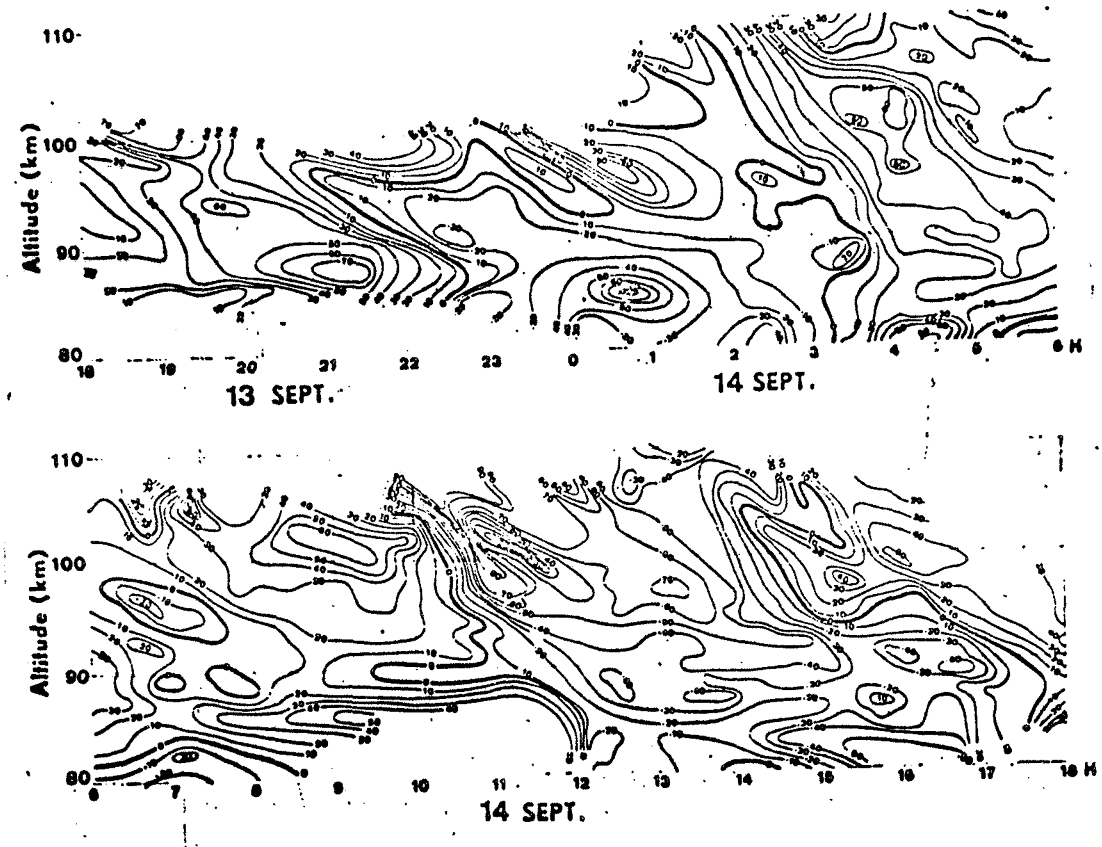

Figure 1. Example of wind profiles provided by the Garchy radar

The variations of the wind are provided as a function of the local time and altitude for the observation run from 13 to 15 September 1966.

Figure 1. (cont.)

Zonal wind
Garchy 13 - 15 Sept. 1966

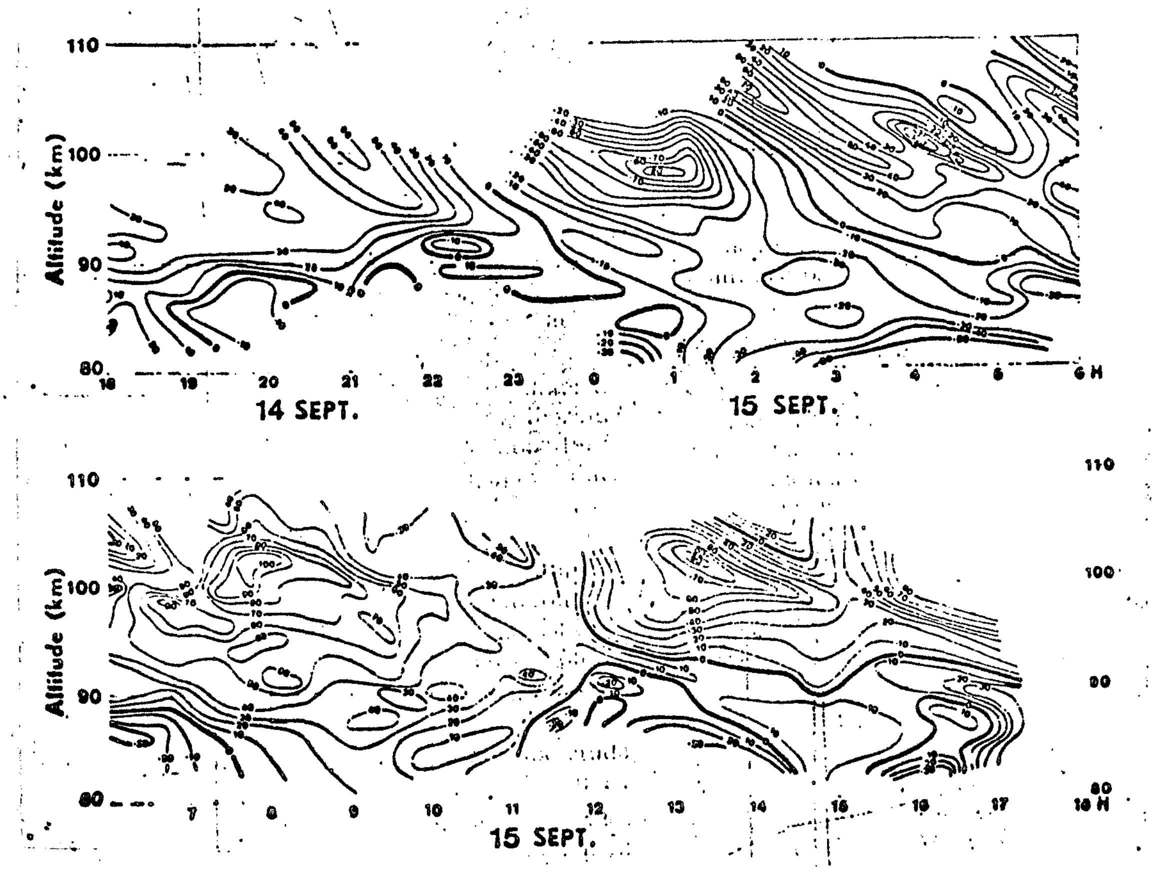

Figure 1. Example of wind profiles provided by the Garchy radar

The variations of the wind are provided as a function of the local time and altitude for the observation run from 13 to 15 September 1966.

of winds as an end in itself. We shall chiefly be concerned with certain of these properties which, compared with theory, appear as anomalies impossible to explain. Their explanation will only be able to be found in the non-linear interactions between the different waves making up the winds. We shall show it first of all in an intuitive manner in paragraph 6 of the present chapter. The demonstration will then be taken up again more in detail in the following chapters.

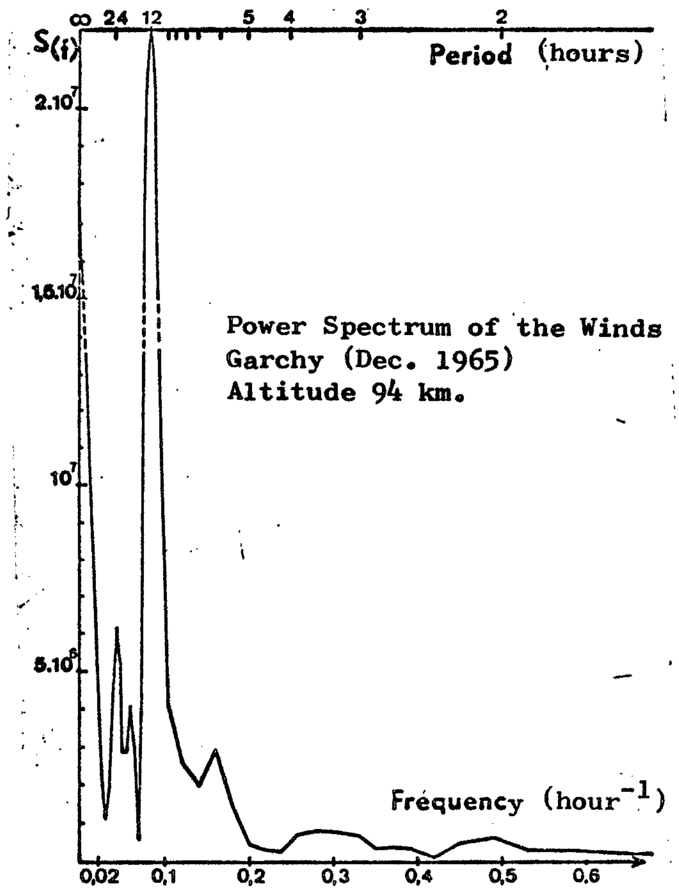

Figure 2. Power spectrum of the wind, Garchy, 29 March - 1 April 1966. (Altitude 94 km.)

The spectral density S(f) expressed in $m^2\ s^{-1}$ is plotted as a function of the frequency f (in hours^{-1}), or of the period τ (in hours). The 4 wind components may be clearly discerned: prevailing wind (A), diurnal tide (B), semidiurnal tide (C), maximum readings corresponding to gravity waves (D).

II. The Components of the Wind

We have seen that most studies published up until now on upper atmospheric winds base their analysis on four independent components:

the prevailing wind, remaining practically constant during an observation period of one or several weeks,

the diurnal and semidiurnal tides, with respective 24 and 12 hour periods,

the small-scale winds; this term will be used to designate the system of components with periods less than 12 hours (no lower limit could be determined experimentally for this period).

Although this way of analyzing winds has been challenged by some authors [Bedinger et al., 1968], it appears difficult to reject it as a whole. It is known, since the first measurements made at Jodrell Bank and Adélaïde (Greenhow and Neufeld, 1961; Elford, 1959 a and b] that a prevailing wind and a tide with a 12 hour period appear in an indisputable way in almost half of the recordings of winds. The diurnal tide appears with a high amplitude at latitudes of 30 to 35° [Elford, 1959 a and b; Hines, 1966]. Nevertheless, the observation of a diurnal tide at Jodrell Bank (53°N) has been the subject of more debate[7]. Also, /8
and particularly, the observations previous to those made at Garchy only supplied some statistical data on small-scale winds, leaving an issue of doubt as to their nature (turbulence or gravity waves?) and proving in no way that they represent a uniform physical phenomenon.

By allowing reconstruction on a continuous basis of wind variations plotted against time, the Garchy radar made possible, for the first time, calculation of the complete spectrum of the winds, from its constant component up to periods on the order of approximately 2 hours, with a precision allowing clear recognition of the different components listed above.

Examples of spectra produced in this way are provided by Figures 2 and 3. It is possible to see here a first confirmation of the existence of these wind

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7. The results obtained at Jodrell Bank were debated by Haurwitz [1961, 1964], who showed that many of them were not significant. More particularly, according to Haurwitz, none of the results relating to the zonal component of the diurnal tide are probably significant.

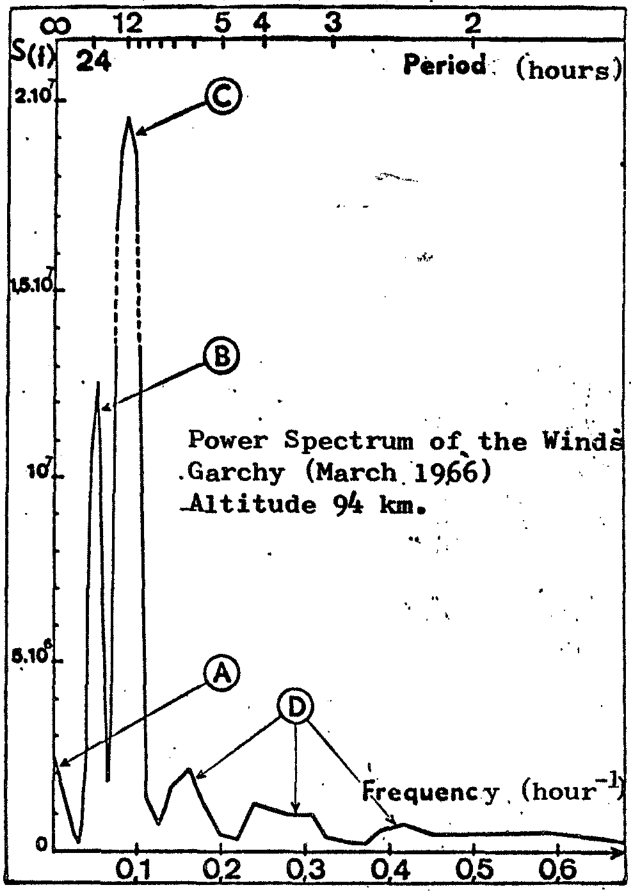


Figure 3. Power spectrum of the wind, Garchy, 14 - 16 December 1965. (Altitude: 94 km.)

As with Figure 2, it is possible to discern the 4 wind components. Nevertheless, the diurnal tide no longer appears as a "peak" of the spectrum but like a component of more complex structure.

components since the latter are quite often reflected by an equal number of distinct maxima of the spectrum. This is, however, not the case with small-scale winds (D) which have several successive maxima as well as periods included between 2 and 10 hours. The only exception: the diurnal tide (B) is often expressed by a maximum too wide to depict a simple spectral line and sometimes divided into two parts.

In order to give an idea of the relative magnitude of these wind components Figure 4 shows the plot of mean energy per unit of mass of each one of them, calculated from the aggregate of observation runs. The energies of the 4 components are comparable except for the one for the diurnal tide which decreases with altitude and represents at 98 km no more than 5% of the total energy of the winds.

III. The Semidiurnal Tide

Of all the wind components, the semidiurnal tide is the best known. This is undoubtedly because, as we shall see, this oscillation has a high amplitude, is very uniform and is, on this account, easy to demonstrate.

The semidiurnal tide exists at all the altitudes between the ground and the ionosphere base. It has been observed on the ground where it appeared as a barometric oscillation [Simpson, 1918; Von Hann, 1918; Haurwitz and Cowley, 1965 and 1966, etc.] as well as in the mesosphere where it was possible to

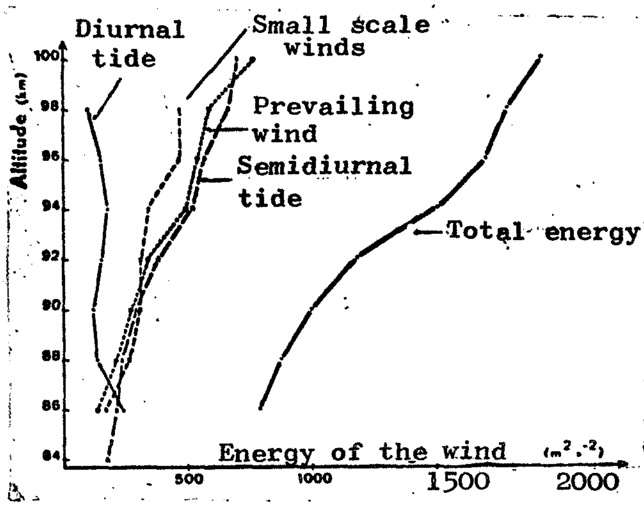


Figure 4. Energy of the different wind components as a function of the altitude.

Mean values calculated from the aggregate of observation runs.

to carry out observations by using aerological rockets [Miers, 1965; Beyers et al; 1965 and 1966; Reed, et al, 1966, etc.]. Finally, it was also observed at the base of the ionosphere where this tide was revealed by observation of meteor trails using the so-called "fadings" method and beginning from artificial clouds. The most complete observations of the semidiurnal tide are those obtained in this last region, i.e., between 80 and 110 km in altitude where its amplitude is high (Figure 4). On the contrary, in the lower atmosphere, this tide only represents a very small proportion of the total energy of the winds, Thus making the observations much longer and less precise. /9

The semidiurnal tide formed the subject of a great number of theoretical studies. Like any oscillation of the whole atmosphere, it has been shown that the result should be a superposition of "modes". One of them, which we shall depict by the symbol S_2^2 can be energized by the heating of the atmosphere owing to solar radiation in the lowest layers of the atmosphere (troposphere, ozonosphere). It is then propagated to the upper atmosphere where a progressive wave should then be observed.

In the following, we are going to examine the properties of the semidiurnal tide experimentally observed and we are going to see that they essentially coincide with those of the theoretical mode S_2^2. These latter properties may be summarized as follows:

1. The mode S_2^2 depicts a coherent oscillation of the whole of the terrestrial atmosphere. At all points of the same altitude its phase is only a function of local time.

2. The oscillation of the wind vector is circularly polarized. The wind rotates in a negative direction in the northern hemisphere and in a positive direction in the southern hemisphere.

3. The progressive wave seen above 80 km, whose energy is propagated upward, should have a phase velocity directed downward. Its phase should rotate by several degrees per km (this value, varying greatly with temperature, corresponds to a vertical wavelength of from about one hundred to several hundreds of km).

4. The amplitude of the tide should increase with altitude z proportionally to exp (z/2H), in which H is the scale of height.

Let us compare these properties to those of the experimentally observed semidiurnal tide:

1. The semidiurnal tide appears as a uniform oscillation, having some degree of phase coherence.

In the spectrum of winds, it appears with a very narrow maximum (Figures 2 and 3) which, taking into account the spectral resolution produced, is not differentiated by an infinitely thin "line" such as would be produced by a pure sinusoidal oscillation.

More precisely, it was possible to confirm, beginning from observations made at Garchy, that the phase of the semidiurnal tide more often then not hardly varied for several consecutive days. As for this, its mean phase $\bar{\Phi}$ was calculated for each run of observations (cf. annex). Then, each one of these runs was subdivided into partial intervals for which its phase Φ_i was calculated. The distribution of the values of phase fluctuation $\Phi_i - \bar{\Phi}$ is provided by Figure 5. These values are, for the most part, less than 20° in absolute value, i. e., on the same order as the error made with Φ_i. The rare exceptions, nevertheless, come from the several runs where the amplitude of the semidiurnal tide is the lowest (April, June II, July), and where, consequently, the measurement can be more easily disturbed by another phenomenon.

During one entire year, the phase and amplitude of the semidiurnal tide show seasonal variations. Nevertheless, from one year to the other, the same values of phase and amplitude may be found approximately in the same season. Greenhow and Neufeld [1961] have confirmed that the same cycle of seasonal variations reappeared for five consecutive years at Jodrell Bank. Similar confirmations were made at several stations using the method of fadings [Rao and Rao, 1964; Briggs and Spencer, 1954; Shimazaki, 1959; Sprenger and Schminder, 1967; Harnischmacher and Rawer, 1968; etc.].

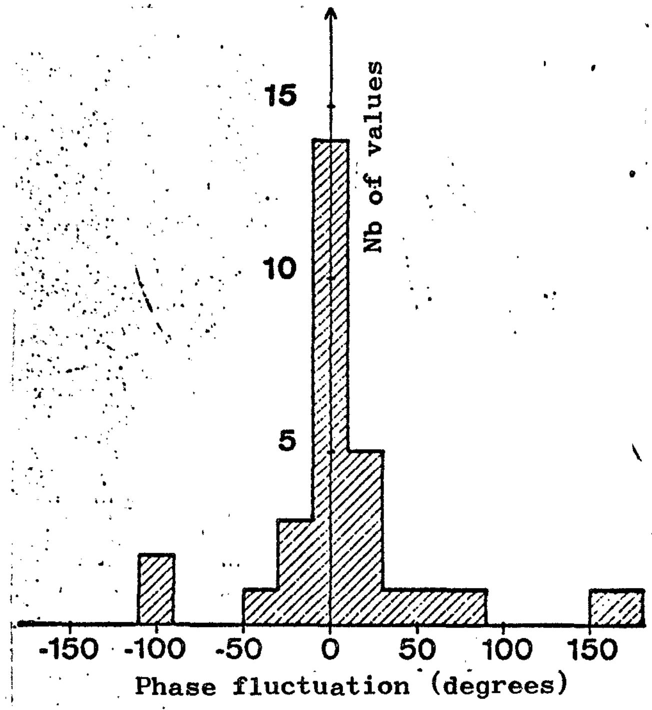


Figure 5. Distribution of values of phase fluctuation $\Phi_i - \bar{\Phi}$ of the semidiurnal tide. (Altitude: 93 km.) The very distinct maximum of this distribution for the zero value illustrates the very great phase stability of the semidiurnal tide.

Finally, in order to confirm the theoretical law according to which the phase of the semidiurnal tide is only a function of local time, it is convenient to depict this phase using local time t_0 at which the tide amplitude is maximum in a specific direction (e.g. to the east). t_0 should be in this case constant for a given altitude and season over the whole earth's surface. Figure 6, including the seasonal variations of the semidiurnal tide observed in the vicinity of 90 km in altitude at several European sites, shows that this law is approximately confirmed, at least from the Atlantic to the Urals. /10

The uniformity of the semidiurnal oscillation in time and space has therefore been confirmed.

2. The circular polarization of the tide, as well as its negative rotation in the northern hemisphere and its positive rotation in the southern hemisphere, have been confirmed at a great number of sites in very varied latitudes, such as:

		(Using a meteor radar)
Jodrell Bank	(53°N)	[Greenhow and Neufeld, 1956 and 1961]
Kharkov	(50°N)	[Kachtcheiev and Lysenko, 1961]
Sheffield	(53°N)	[Muller, 1966]
Adêlaide	(35°S)	[Elford, 1959 a and b; Elford and Robertson, 1953]
		(Using the method of "fadings")
Halley Bay	(76°S)	[Piggott and Barcley, 1962]
Kjeller	(59°N)	[Harang et al., 1957 and 1964]
Lower Hult	(41°S)	[Henderson, 1963]
Yamagawa	(31°N)	[Shimazaki, 1959; Tsukamoto, 1959]

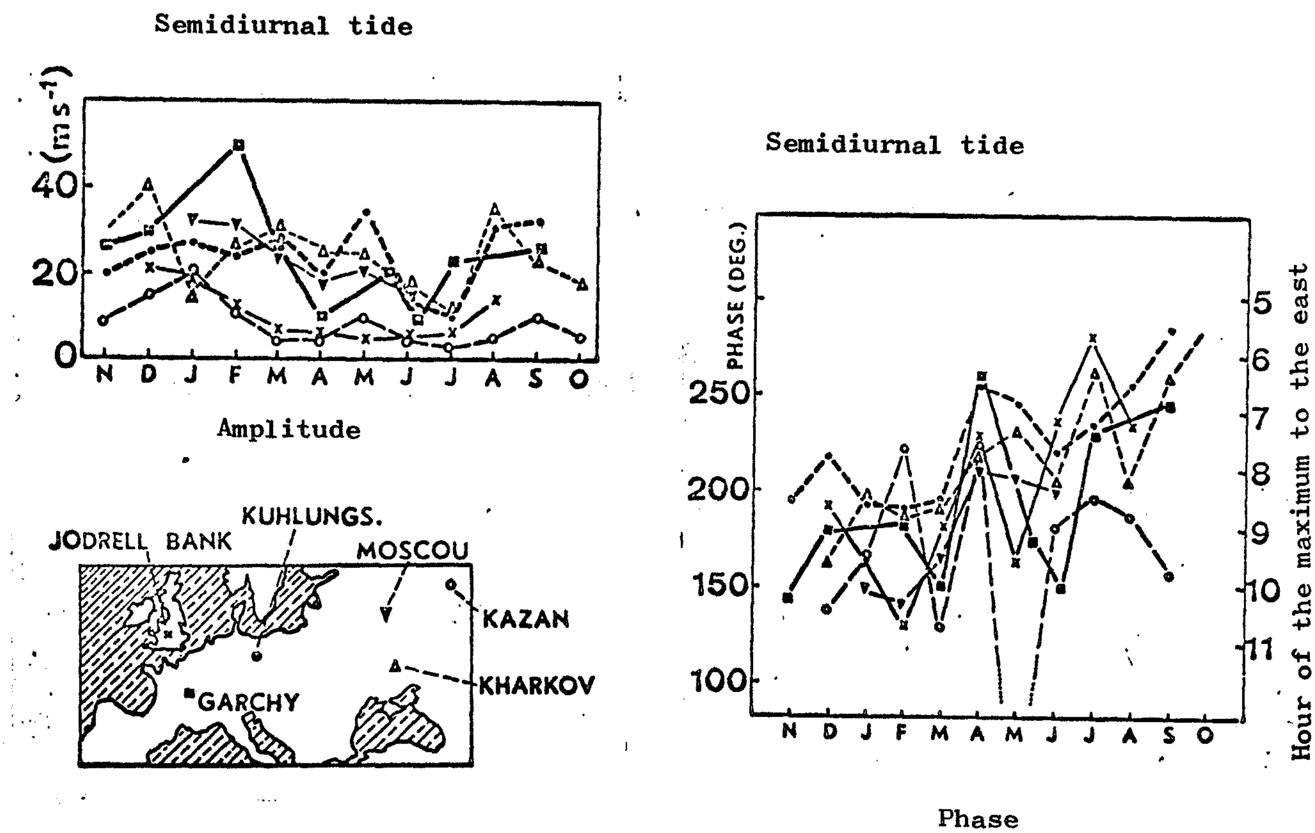


Figure 6. Seasonal variations of amplitude and phase of the semidiurnal tide observed by different European sites:

Garchy [Revah, 1969], Kuehlungsborn [Sprenger and Schminder, 1967], Jodrell Bank [Greenhow and Neufeld, 1961], Kharkov [Kachtcheiev and Lysenko, 1961], Moscow and Kazan [Zadorina et al., 1967].

Although there are some exceptions, they almost always appear at periods of the year and at latitudes in which the semidiurnal tide has a lower amplitude (in summer for the mean latitudes [Greenhow and Neufeld, 1961], and in low-latitude sites such as Waltair, 18°N [Rao and Rao, 1964]; Delhi, 28°N [Mitra and Viz, 1960]), i.e. under conditions in which measurements are the most disturbed.

3. Experience has confirmed that the semidiurnal oscillation is propagated downward. According to measurements made at Jodrell Bank in 1953 - 1958 [Greenhow and Neufeld, 1956 and 1961], its phase increases with altitude on the average of 5° per km (3° per km in summer, 7° per km in winter).

The same observation was made in 1956 - 1966 beginning from the Garchy radar, but with a better definition in altitude. Figures 7 to 15 provide the variations of amplitude and phase of the semidiurnal tide as a function of altitude for each one of the observation runs. A margin of error has also been plotted on this figure. /11

Figures 7 to 15 show that phase Φ of the semidiurnal oscillation has a tendency to increase with altitude z, although it deviates significantly from the linear increase which should yield a pure mode S_2^2. A mean slope $d\Phi/dz$ has been defined for each run and represents the straight line of regression. These values of $d\Phi/dz$, plotted on Figure 16, are probably in acceptable agreement with those of Greenhow and Neufeld, with the exception of aberrant values found in March and April (in April, the straight line of regression has hardly any direction). A simultaneous explanation could be made of these aberrant values (many of them likewise in the data of Greenhow and Neufeld) and the deviation of $\Phi(z)$ with respect to a linear law, by allowing other weaker oscillations with different wavelengths to be superposed on the chief mode S_2^2. It is worthy of notice in behalf of this explanation that:

(a) The runs in which $\Phi(z)$ deviates the most from a linear law (April, June II), and in which the values of $d\Phi/dz$ appear aberrant, are those in which the amplitude of the tide (therefore: of the chief mode S_2^2) is the lowest.

(b) Instead of a simple spectral analysis of the winds, it is possible to carry out a "two-dimensional" analysis supplying a spectrum with two dimensions, function of frequency and number of waves. The two-dimensional spectrum has the advantage of allowing separation of two components with the same period and different wavelengths. Now, the two-dimensional analysis confirms the existence of a dominant component in which $d\Phi/dz$ coincides with the slope of the straight line of regression (Figure 16), for all runs, except for March and April where the presence of several components appears significantly.

4. The last property of S_2^2 predicted by the theory is the increase of its amplitude v with altitude z, proportionally to exp (z/2H).

When H = 6.5 km, the amplitude v of the semidiurnal tide should therefore increase tenfold approximately every 30 km, which appears to be well in agreement with the orders of magnitude of v observed, not only above 80 km, but also below

November 1965 Period component 12 hours

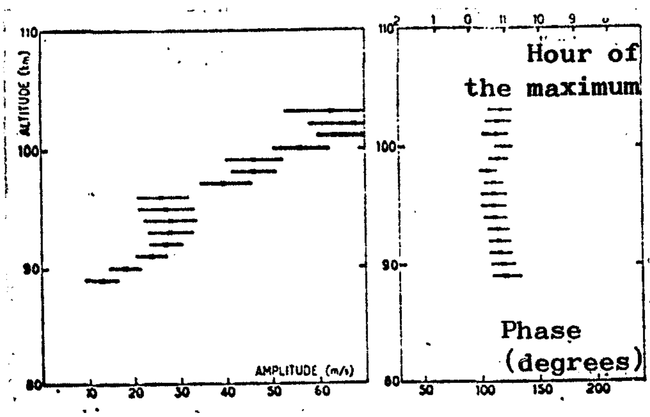


Figure 7

December 1965 Period component 12 hours

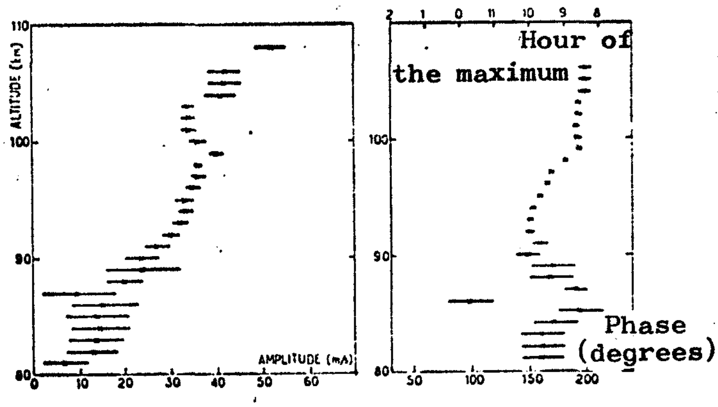


Figure 8

February 1966 Period component 12 hours

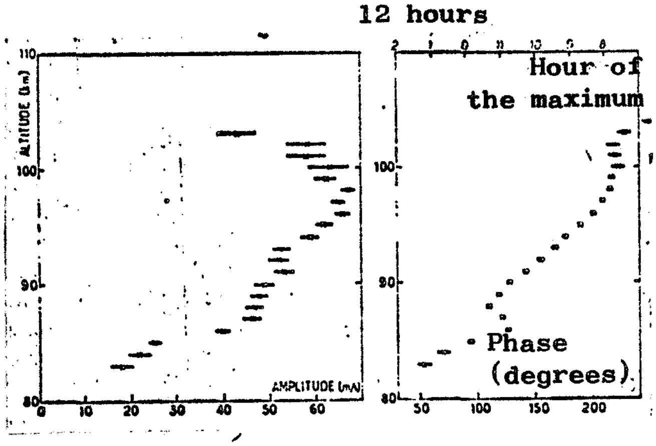


Figure 9

March 1966 Period component 12 hours

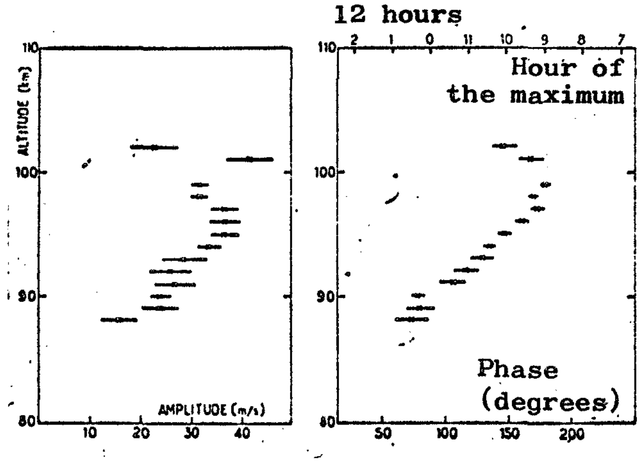


Figure 10

April 1966 Period component 12 hours

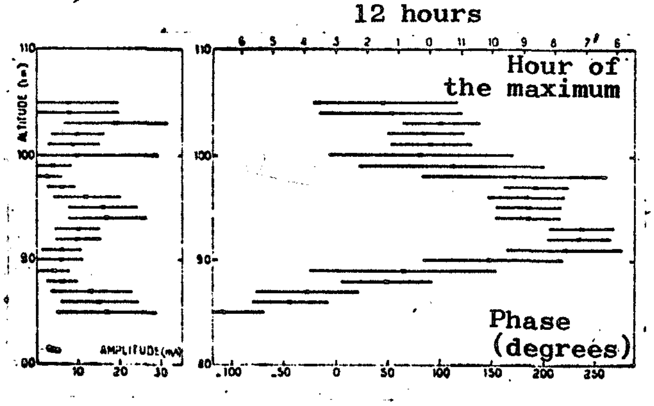


Figure 11

Figure 7 to 15. Phase and amplitude of the semidiurnal tide observed at Garchy, from November 1965 to September 1966.

Figures 7 to 15 (cont.)

/12

8-10 June 1966 Semidiurnal tide

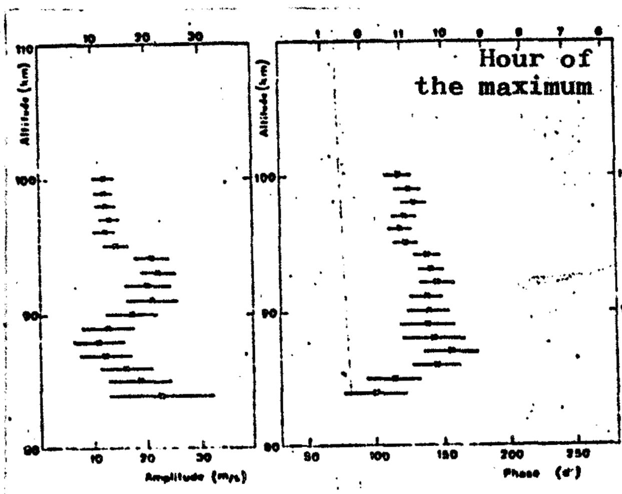


Figure 12

21-24 June 1966 Semidiurnal tide

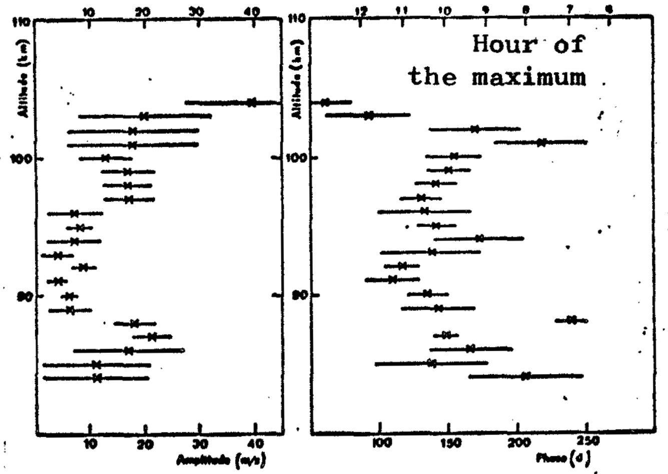


Figure 13

19-22 July 1966 Semidiurnal tide

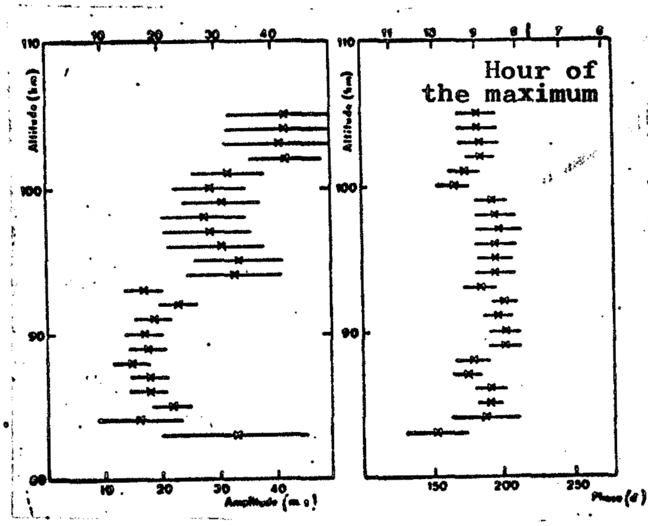


Figure 14

13-15 September 1966 Semidiurnal tide

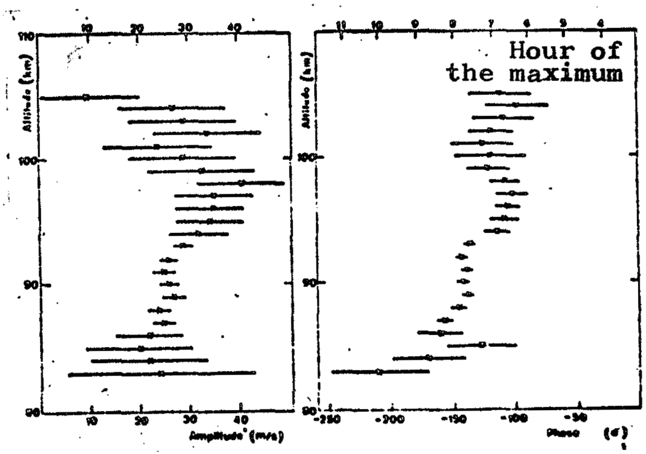


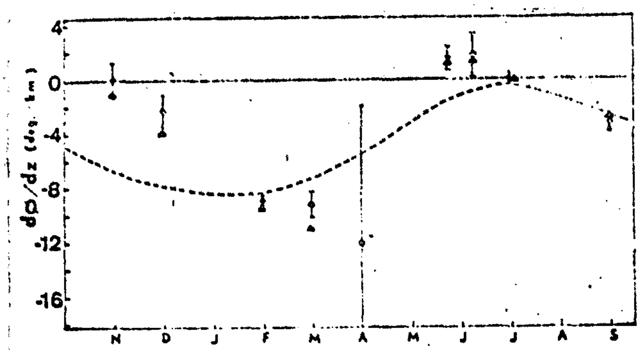
Figure 15

Figures 7 to 15. Phase and amplitude of the semidiurnal tide observed at Garchy, from November 1965 to September 1966.

this altitude.

z = 40 km	v = 0.3 to 1 m/s	(aerological rockets)
60 km	2 to 8 m/s	
80 km	10 to 20 m/s	(meteor trails)
100 km	20 to 60 m/s	

Semidiurnal tide: seasonal variations of the vertical phase gradient.



Garchy: slope of the straight line of progression.

▲ Garchy: wavelength deduced from the two-dimensional analysis.

Jodrell Bank: mean curve.

Figure 16. Seasonal variations of the vertical phase gradient $d\Phi/dz$ of the semidiurnal tide (or: of the equivalent vertical wave length $\lambda = 2\pi\ (d\Phi/dz)$).

The agreement can appear acceptable between the values obtained at Garchy in 1965-1966 and those obtained at Jodrell Bank from 1953 to 1958, on condition of not taking into account values obtained at Garchy in April at the same time taking the slope $d\Phi/dz$ of the straight line of regression. These aberrant values are not confirmed by the two-dimensional harmonic analysis, showing that in these cases the tide cannot be reduced to a simple wave with a given wavelength. Its structure is more complex.

Garchy [Revah, 1969]; Kuhlungsborn [Sprenger and Schminder, 1967], Jodrell Bank [Greenhow and Neufeld, 1961], Kharkov [Kachtcheiev and Lysenko, 1961], Moscow and Kazan [Zadorina et al., 1967].

This only represents an approximate verification. In reality, the data coming from rockets and meteors were produced in different places and the meteorological rockets supplied only little data on the semidiurnal tide [Lenhard, R. W., 1963; Beyers, et al., 1966; Reed, et al., 1966].

Beginning from winds measured at Jodrell Bank by meteor trails, Greenhow and Neufeld [1956, 1961] calculated the mean values of the dv/dz gradient between 80 and 100 km and studied their seasonal variations. Their results, plotted on Figure 17, are confirmed by those obtained at Garchy (plotted on the same figure). It may be noted that dv/dz is practically zero during summer, this appearing to be incompatible with the above exponential law. /13

In order to try a more valid comparison, an attempt was made to approximate the experimental values of (z) observed at Garchy by an exponential law in the form: $v \propto \exp(\alpha z)$ (a method of least squares was used for this). The following conclusions resulted:

(a) during winter months, α does not differ significantly from its theoretical value 1/2 H,

(b) during summer months (June to September, α is less, to a significant degree, than this theoretical value,

(c) the experimental values of the wind v(z) almost always deviate significantly from the exponential law defined above. Here again, everything occurs as if other oscillations with different wavelengths were superposed to the S_2^2 mode.

In conclusion, the properties of the experimentally observed semidiurnal tide deviate very little, between 30 and 100 km in altitude, from those of the theoretical S_2^2 mode. The rare disagreements between experience and theory appear most often when the amplitude of this tide is at the minimum, and therefore can be explained by the superposition, in the chief S_2^2 mode, of other lower amplitude oscillations. The only disagreements between observations and theoretical laws concern the variations as a function of the altitude, amplitude v and phase Φ of the semidiurnal tide. The slopes dv/dz and dΦ/dz show great seasonal variations and occasionally have values disagreeing with the theoretical law (dv/dz in summer). Yet the theoretical laws referred to above ($v \propto \exp(z/2H$, $d\Phi/dz$ = constant) are only strictly applied to an isothermal environment. Now, the presence of a temperature minimum in the vicinity of 80 km greatly modifies the laws of variations of v and Φ as a function of z, and make them very sensitive to the least variations of the temperature profile. Beyond any doubt, none of the properties of the experimentally observed semidiurnal tide is in flagrant

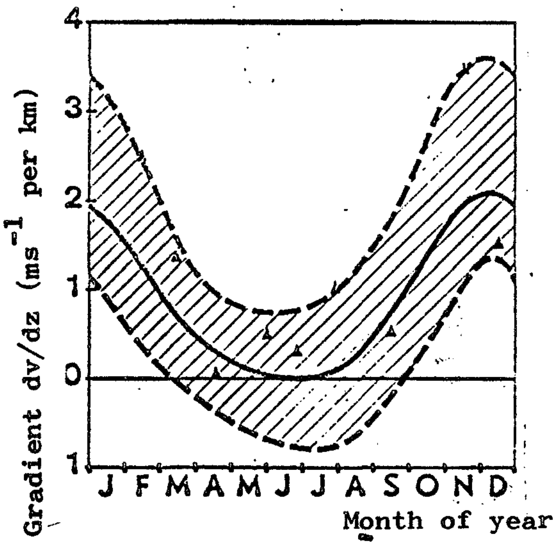


Figure 17. Seasonal variations of the vertical gradient dv/dz of the amplitude of the semidiurnal tide.

A comparison was made between the data taken by the Garchy radar (triangles) and those from Jodrell Bank (included in the crosshatched zone) disagreement with the hypothesis of a predominance of the S_2^2 mode.

IV. The Diurnal Tide /14

The contrast is striking between the semidiurnal tide studied in the previous paragraph and the diurnal tide which we are going to examine. The semidiurnal tide appears as a uniform, stable oscillation which can be demonstrated by a simple theoretical model. On the contrary, the diurnal tide shows, especially at middle latitudes, non-uniform fluctuations. Also, the latter tide does not allow itself to be reduced to a simple model.

It is probably for this reason that reports on the diurnal tide are less common than those written on the subject of the semidiurnal tide. Nevertheless, these are the same experiments which allow observation of both phenomena to a fairly accurate degree. For this reason, the diurnal tide, very slight at ground level, is more difficult to show beginning from barometric oscillations. On the contrary, its high amplitude between 30 and 60 km simplifies its study by means of aerological rockets [Miers, 1965; Beyers et al., 1965 and 1966; Reed et al., 1966; Webb, 1966 a and b, 1967]. The most copious data concerning diurnal tide were obtained between 80 and 110 km by the observation of meteors and by the "fadings" method. Finally, observation of luminescent clouds supplied some data between 90 and 130 km [Hines, 1966].

The theory of the diurnal tide derives from the Laplace equations as does the semidiurnal theory. Also, it is believed that both these theories chiefly differ quantitatively from each other, owing to the different value of the period, although not having a basic character. In particular, any diurnal oscillation of the atmosphere can be reduced to the sum of several "modes" whose chief properties are the following:

1. the phase at a given point does not vary with time, provided this mode is itself energized by a time-stable energy source (solar radiation) and provided that the characteristics of the atmosphere have no great variations;

2. the rotation of the wind vector is carried out, at a given latitude, always in the same direction. With respect to the modes of the diurnal tide, the wind vector always rotates in the negative direction in the northern

hemisphere;

3. the vertical wavelength is only a function of the mode considered. It amounts to 27 km for the first S_1^1 mode[8], and less than this value for modes of a higher order;

4. in the absence of scattering (this is the case for the S_1^1 mode below 110 km), the specific energy of a mode varies, as a function of altitude z, like exp (z/H).

To these properties, which recall point by point those of the semidiurnal tide described in paragraph 3, we shall add one more which is characteristic of the diurnal tide:

5. there are two types of S_1^n modes:

those for which n > 0 are vertically propagated as one wave. They have a high amplitude at latitudes less than approximately 30°, this amplitude quickly decreasing when the latitude increases above this value.

those for which n < 0 are not vertically propagated. When the altitude increases, their amplitude decreases exponentially and their phase remains stationary. These modes have a high amplitude at latitudes greater than 30°, this amplitude quickly decreasing when the latitude decreases below this value.

The study of the experimental properties of the diurnal tide will be carried out in several stages. We shall at first proceed, exactly as in the case of the semidiurnal tide, by making an experimental comparison of each one of the above theoretical properties. This procedure is conventional but the result will be deceptive. Theory only very incompletely takes experimental results into account. We shall propose in this case, using a second time a method better suited to the study of the diurnal tide and which is based on the observations recently carried out at Garchy.

We shall first study the tide between 80 and 130 km in altitude, then below 80 km (where its properties are quite different).

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8. This mode is designated by S_1^3 in the articles by Lindzen. The vertical wavelength is a function of the atmospheric temperature and the value 27 km corresponds to a temperature of 250°K.

A. Diurnal tide between 80 and 130 km. Comparison between experimental data and theoretical "modes".

1. The diurnal tide is not a pure sinusoidal oscillation.

Between 80 and 110 km in altitude, at middle latitudes, its amplitude and phase show non-uniform variations and it cannot be assimilated to a simple spectral line without committing a serious error.

This appears clearly when examination is made of the wind spectra provided by the Garchy radar. Figure 18 provides a few examples of this. The spectrum obtained in February has, in the case of one 24 hour period, a maximum whose width is on the order of the spectral resolution (approximately 2.10^{-2} $hour^{-1}$)[9] and which, consequently, is not differentiated by an infinitely thin spectral line. This case is exceptional. More often than not, the diurnal tide occupies a maximum bandwidth perceptibly greater than the spectral resolution (December). /15 Or again, the maximum appears for a different 24 hour period which can vary between 17 hours (April) and 30 hours (September). On the mean spectrum calculated from the aggregate of nine recording runs (Figure 19), the diurnal tide no longer appears as a very clearcut maximum but as a blurred maximum occupying the range of periods included between approximately 17 and 35 hours.

This absence of discontinuity will lead us, in the following, to terms as "diurnal tide" the whole of the oscillations of the wind included in this range of frequencies (any other boundary would appear as completely arbitrary). This definition will subsequently be given its physical justification since these oscillations have specific properties in common (vertical wavelength).

Greenhow and Neufeld [1961] have noted that at Jodrell Bank (53°N) the amplitude and phase of the diurnal tide vary considerably from day to day. This amounts to saying that this tide occupies a wide bandpass. However, these writers do not exploit fully all the consequences of this observation. They determine the characteristics of tides by assimilating them on a preliminary basis to spectral lines which procedure is false in the case of the

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9. The spectral resolution is on the order of 1/T, where T is the duration of the sample tested.

Energy spectrum of the winds.
Garchy - Altitude 94 km

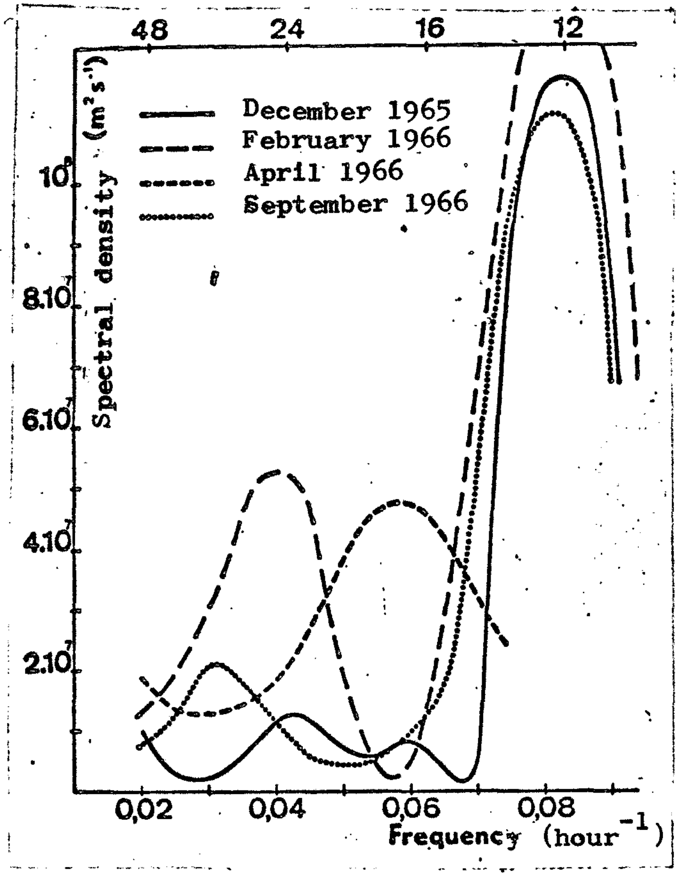

Figure 18. Some examples of spectra of winds obtained at Garchy for frequencies in the vicinity of that found for the diurnal tide (altitude: 94 km.)

It may be ascertained that the maximum of the spectrum hardly ever appears for a 24 hour period. (The spectral definition is on the order of 2.10^{-2} $hour^{-1}$.)

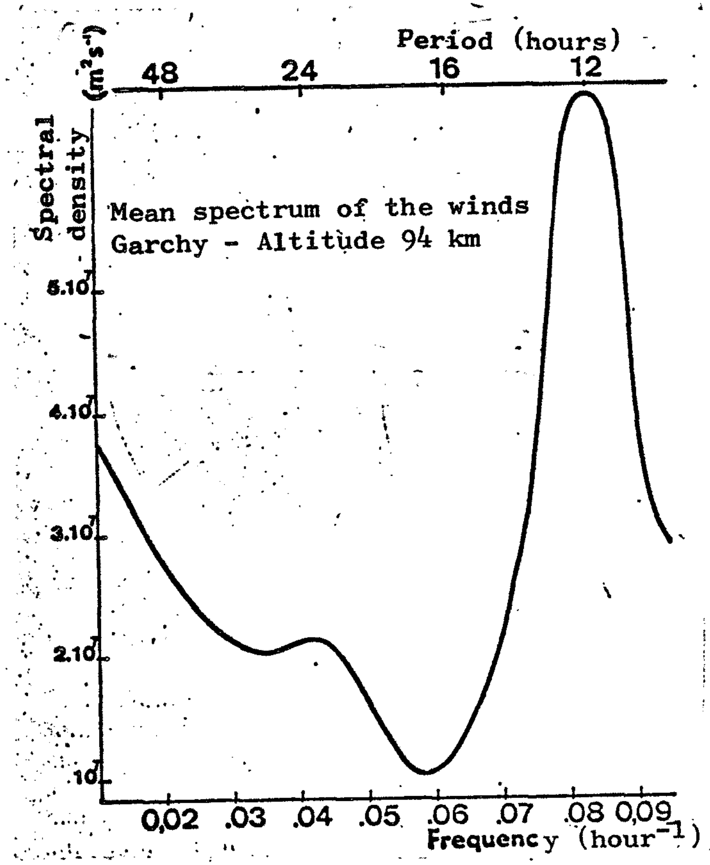

Figure 19. Mean spectrum o of winds produced at Garchy, calculated on the aggregate of the 9 recording runs. (altitude: 94 km.)

The diurnal tide does not appear as a clearcut maximum of the spectrum.

diurnal tide. And, what is more, all writers making use of observations of meteors or the "fadings" method proceed in the same way.

Let V_T be the amplitude of this tide, calculated as if it were a matter of a spectral line, e.g., beginning from:

$$V_T = \frac{1}{T}\int_{-\frac{T}{2}}^{+\frac{T}{2}} u(t)e^{-2\pi jft}dt$$

where u(t) is the wind and T the duration of the sample, assumed to be a multiple of the period. It is shown that V_T has no simple physical significance but that $|V_T|^2$ is approximately the energy of the wind included in a frequency band with width 1/T around the central frequency of the tide. Since the diurnal tide occupies the range of periods included between 17 and 35 hours, or a frequency band with width $\Delta f = 3.10^{-2}$ hour^{-1}, it follows that: /16

in the case of a sample with duration T = 24 hours, 1/T is on the order of Δf and $|V_T|^2$ represents an order of magnitude of the energy of the diurnal tide with an error not exceeding 20% in the worst case (which, however, is generally less than this value). The estimates which we shall provide in the following (and those already shown on Figure 4) were obtained in this way.[10]

in the case of a sample with duration T greater than 24 hours, $1/T < \Delta f$, hence $|V_T|^2$ only represents a fraction of the total energy of the diurnal tide, this fraction becoming proportionally smaller as duration T of the sample grows larger. This could explain, for example, why the "amplitude" of the zonal diurnal tide given by Greenhow and Neufeld [1956, 1961] varies according to whether it is calculated based on one day (it is in this case sometimes greater than the amplitude found for the semidiurnal tide), or whether it concerns a mean calculated over a period of two to three days (it varies between 5 and 20 ms^{-1}), a seasonal mean (2 to 4 m/s) or an annual mean (non-significant values). It can be seen that it is not easy to attribute a physical meaning to such data. Unfortunately, the same comment is valid, not only for Jodrell Bank but also for other middle latitude sites (Kharkov, Kazan, etc.), where

10. The mean of the values of $|V_T|^2$ is subsequently calculated from several samples in order to reduce the error.

the diurnal tide was calculated according to the same principle.

At lower latitudes, the non-uniform characteristic of the diurnal tide appears less marked. At Adélaïde (35°S), its phase and amplitude also reveal strong fluctuations [Elford, 1959 a and b]. Nevertheless, the mean spectrum of the diurnal tide shows, contrary to the spectrum obtained at Garchy, a strong maximum for a 24 hour period. The existence at such latitudes of a diurnal tide with a relatively stable phase is also confirmed by a study of Hines [1966] using measurements of winds by artificial clouds at Wallops Island and Sardinia (38°N).

2. Polarization of the diurnal tide.

The great many measurements made at Jodrell Bank (53°N) and Adélaïde (35°S) show that the diurnal tide successively shows all polarizations possible since the wind vector rotates both in the positive as well as in the negative direction. In Adélaide [Elford, 1959 a and b], this direction of rotation frequently varies with the altitude which fact, from the viewpoint of the "modes" theory, is completely incomprehensible.

Nevertheless, the cases in which the wind rotates in the direction predicted by the theory are the most frequent ones and the winds derived from annual means have a direction of rotation consistent with theory.

3. Wavelength of the diurnal tide.

No propagation phenomenon of the diurnal tide could either be observed at Jodrell Bank or Adélaïde. Its phase, on the contrary, appears to vary randomly with the altitude [Greenhow and Neufeld, 1961; Elford, 1959 a and b). However, these experiments only provide a mean value of the phase in three or four consecutive altitude intervals which can be insufficient to reveal a propagation (above all when the latter is disturbed).

The measurements made at Garchy confirm in most cases the absence of a simple propagation with linear variation of phase. Nevertheless, for some runs (see, for example, Figure 20), there may be seen a linear increase of this phase, indicating a propagation with a phase velocity directed downward

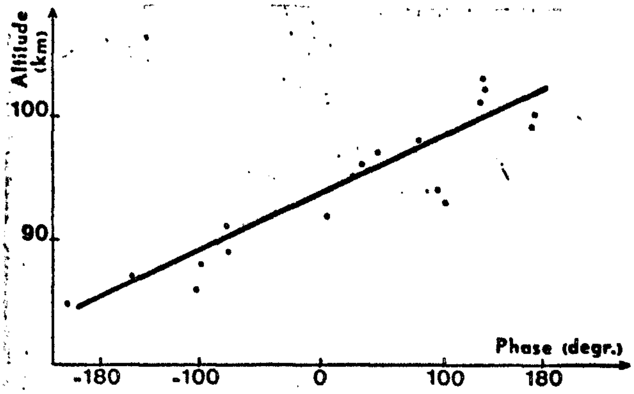

Figure 20. Phase of the diurnal tide as a function of altitude. Garchy, 14 - 16 December 1954;

One of the rare examples showing an oscillation, with a 24 hour period, which is propagated with a vertical wavelength. An agreement with theory such as this is exceptional.

and a wavelength of 20 to 30 km.

A statistical study involving about thirty artificial clouds [Hines, 1966] (observation method likewise providing a good definition in altitude) also leads to a mean vertical wavelength of the diurnal tide of 20 to 25 km.

The results described up to now suggest the existence of a diurnal tide whose mean characteristics are those of the theoretical modes with predominance of the S_1^1 mode, but of which the propagation appears greatly disturbed.

Unfortunately, the situation becomes more complicated with the appearance of mean characteristics of the diurnal tide which are quite different from those /17 predicted on a theoretical basis for the S_1^1 mode.

4. Variation with altitude of energy of the diurnal tide.

The S_1^1 mode should theoretically be propagated below 105 km without either dissipation or reflection. Its energy per unit of volume should therefore not vary with altitude z. Its energy per unit of mass therefore varies as exp (z/H). Or again, its amplitude (to the extent in which it has a physical meaning, see 1, above) varies as exp (z/2H). When H = 6.5 km, the energy per unit of mass of this tide should therefore increase tenfold every 15 km.

Now, Figure 4 shows that at Garchy the mean energy per unit of mass of the diurnal tide varies only slightly with altitude. The observations made at Adélaïde [Roper, 1966] lead to the same conclusion. If it is assumed that the group velocity of this tidal wave is directed upwards (see 3, above), this wave is propagated losing energy at the same time.

5. Variations of amplitude of the diurnal tide with latitude.

We have seen that a characteristic property of the S_1^n modes of positive n in general - and of the S_1^1 mode in particular - is their large value in the lower latitudes. Let us see if this property is confirmed experimentally.

The winds measured by meteor radar are on the order of 10 to 50 m/s at Adélaïde (35°S) whereas the sites in latitudes included between 45 and 60° (Garchy: 47°N, Kharkov: 50°N, Jodrell Bank: 53°N, Sheffield: 53°N, Kazan: 56°N) give amplitudes of 2 to 15 m/s (Figure 21).[11]

Using the "fadings" method, there is obtained at Waltair (18°N) a diurnal tide with a very high amplitude (70 to 80 m/s). However, this site is unfortunately the only one at a very low latitude. In addition, the measured amplitude is very variable from one site to another (Figure 21). This dispersion of results, moreover, may be explained by the often debatable manner in which the tidal amplitude is defined (see 1 above), and by the variations, during one day, of the altitude of ionospheric reflections.

In spite of the dispersion and insufficiency of these results, we can only conclude - on a provisional basis - that the amplitude of the diurnal tide is greatest at lower latitudes and that, consequently, the modes of positive n prevail.

In conclusion:

(a) the experimental study of the diurnal tide most often causes the

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11. Figures 2-22 summarize the results produced for the zonal diurnal tide by 6 sites using meteor radars (mentioned above), and by 15 sites using the "fadings" method: Waltair, Delhi, Kjeller, Tomsk, Cutwick, Irkoutsk, Cambridge, Fribourg, Rostov, Simeiz, Yamagawa, Brisbane, Wellington, Ashkabad, Halley Bay. [Kachtcheiev and Lysenko, 1961; Greenhow and Neufeld, 1956 and 1961; Muller, 1966; Zadorina et al, 1967; Rao and Rao, 1964; Mitra and Vix, 1960; Harang and Pedersen, 1957; Kazimirovski and Koukourov, 1961; Briggs, et al., 1950; Shimazaki, 1959; Tsukamoto and Ogata, 1959; Rao and Rao, 1965; Piggott and Barclay, 1962].

appearance of characteristic properties of the S_1^n of $n > 0$,

(b) these properties are more or less masked by nonuniform fluctuations of all the characteristics of the diurnal tide and more particularly by its period,

(c) the energy of the diurnal tide is propagated upwards with heavy dissipation.

Amplitude of the zonal component of the diurnal tide at various sites.

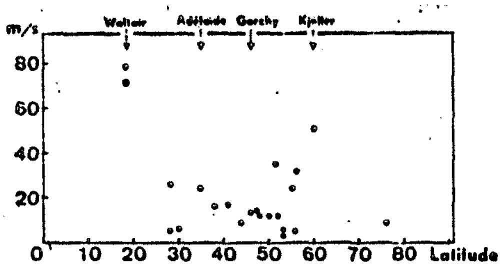


Figure 21. Amplitude of the zonal diurnal tide as a function of latitude.

Summary of published observations using meteors (Jodrell-Bank, Kharkov, Garchy, Adélaïde) or the "fadings" method (20 different sites).

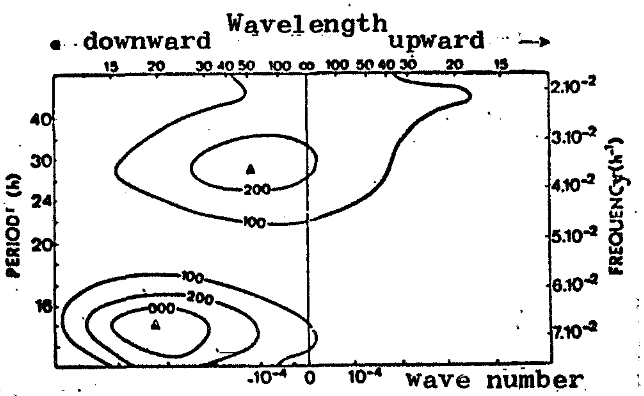
Let us recall that the modes which have a positive n are propagated vertically like a wave. Their preponderance (a) in modes with negative n (in which energy is not propagated vertically) therefore means that the diurnal tide which is propagated beginning from an external energy source prevails, between 80 and 130 km, over the one which is locally energized.

The two other properties (b) and (c) represent as yet unexplained anomalies. We return to them later on.

B. Diurnal tide between 80 and 130 km: analysis of the fine structure of the spectrum.

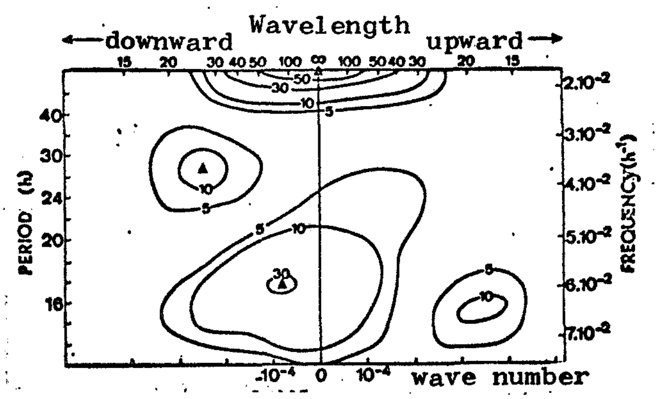
The analysis of the diurnal tide made above remains, in spite of these results, rather deceptive. The theoretical model proposed only very crudely takes experimental results into account and it is the latter which still most often remain unexplainable in their details.

The results supplied by the Garchy meteor radar suggest another way of approaching this study. Since the diurnal tide may not be reduced to a simple spectral line, the start will be made by a Fourier analysis of the problem. We shall see that it is possible in this way to separate the diurnal tide into



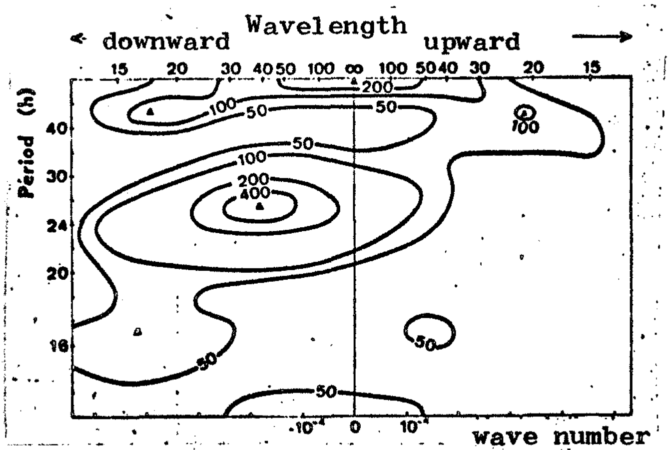
November 1965

Figure 22



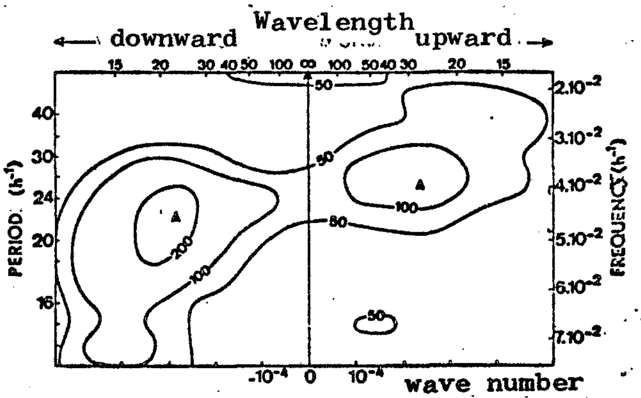
December 1965

Figure 23



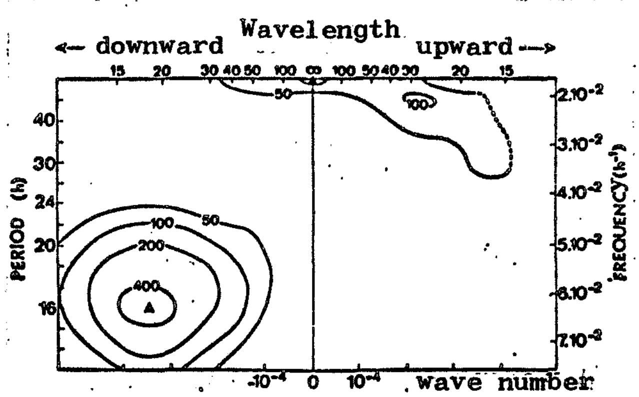
February 1966

Figure 24



March 1966

Figure 25



April 1966

Figure 26

Figures 22 to 30. Two-dimensional spectral analysis of the winds measured at Garchy.

Figure 22 to 30 (cont.)

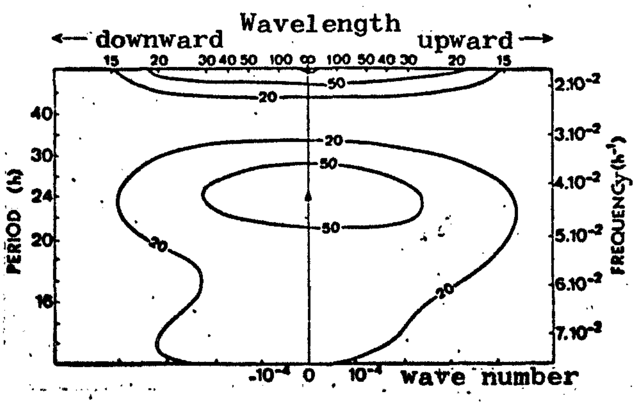


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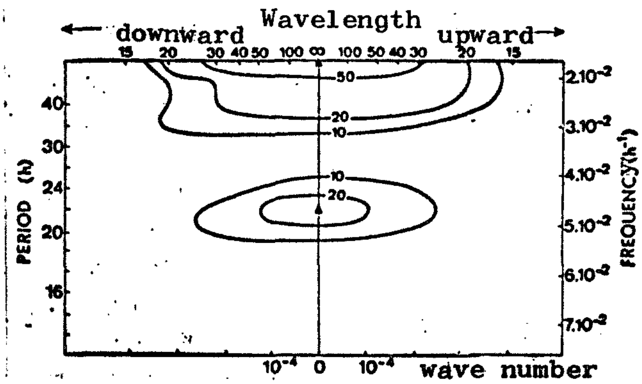
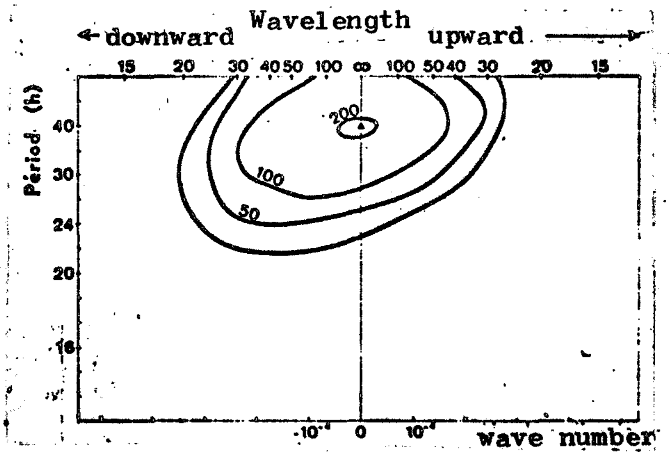
Figure 27



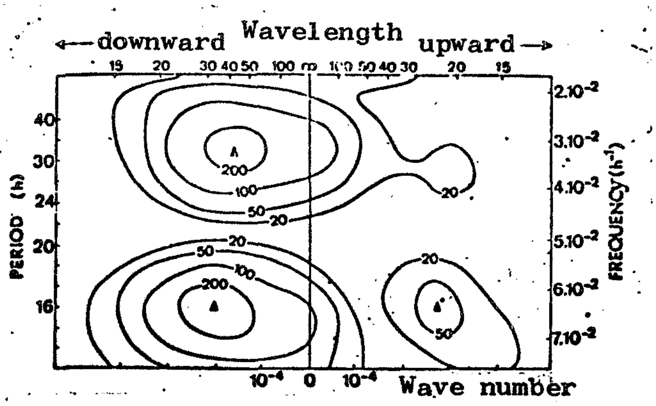
June II 1966

Figure 28



July 1966

Figure 29



September 1966

Figure 30

Figures 22 to 30. Two-dimensional spectral analysis of the winds measured at Garchy several distinct oscillations having different physical significances. Unfortunately, it was only possible to apply this method to the Garchy data. /19

Beginning from profiles of winds produced at Garchy, it is possible to calculate the two-dimensional energy spectrum of the wind S(f, k) (f: frequency, k: vertical wave number). It is shown that, whenever a wind results from the superposition of several sinusoidal waves f_n, k_n, a maximum of the calculated spectrum S(f, k) corresponds to each one of these waves.

Figures 22 to 30 show the two-dimensional spectra deduced from the winds observed at Garchy. They all show several distinct maxima and it is possible to confirm that the shape of these maxima almost always coincides with the one which would be given by a pure sinusoidal wave. It therefore appears possible, at least as a first approximation, to consider the diurnal tide as the sum of several pure sinusoidal waves.

There are not yet enough Garchy observations to allow a systematic study of these waves. However, it already appears that it is possible to classify them into three different families according to their direction of propagation:

1. most of these waves are propagated downwards, corresponding to a propagation of energy upwards (negative k). They have in this case very variable periods ranging from 16 to 30 hours as well as wavelengths often included between 20 and 30 km,

2. some of the waves of the above type are accompanied by a wave with a lower amplitude, but with the same period. This wave has a wavelength which is close to that of the above but is propagated in the reverse direction (March, September) as if it were a matter of a reflected wave,

3. finally, the runs of June and July show a component which is not propagating (k = 0), and therefore the period is in the vicinity of 24 hours.

The waves of the first type, through their properties, come close to the positive n modes of the diurnal tide with one possible difference in period which remains to be explained. Since these waves are preponderant, it is understood why the properties of the positive n modes often appear experimentally.

The presence of oscillations of the third type suggests that there could be, in addition to tides being propagated like a wave, a diurnal tide locally energized by solar heating.

C. Diurnal tide below 80 km.

The diurnal tide between 30 and 60 km in altitude is only known through the results from several series of launches of meteorological rockets. Very little data is presently available and, with a few exceptions [e.g. Reed et al., 1966], only concern latitudes below 35°. They hardly allow the drawing of final conclusions. They show at best that the properties of the diurnal tide above 80 km are no longer necessarily valid below this altitude.

No experimental data on the diurnal tide between 60 and 80 km is available. Nevertheless, it is possible to compare the data supplied by meteors at 80 km (lower limit of this observation method) with those taken from rocket launches. The following table shows results of observations made at comparable latitudes:

Altitude	Amplitude of the diurnal tide	Observation site	Latitude
80 km	80 to 40 m/s	Adélaide	35°S
60 km	2 to 10 m/s	White Sands	28.5°N

These orders of magnitude are compatible with the theoretical law according to which the amplitude should increase proportionally to exp $(z/2H)$ (according to this law, the amplitude should quadruple between 60 and 80 km). It therefore appears that, contrary to what occurs above 80 km, the diurnal tide is propagated below 80 km without losing any or very little energy.

On the other hand, the irregular character of the diurnal tide is less ob- /20 vious between 30 and 60 km than at high altitudes. Figures 31 and 32 show a comparison of variations of the phase of the diurnal tide as a function of altitude, for sites at similar latitudes at different periods of the year. The curves produced show a great similarity, revealing in this way a great phase stability of this tide both in time and in space. At the same time, the uniform increase of phase with altitude shows that, as at higher altitudes, there is propagation of energy upwards.

In conclusion, it is only above 80 km that two great similarities of the diurnal tide are observed:

the non-uniform variations of its phase which, at medium latitudes, can appear as an appreciable frequency drift;

its propagation upwards with a wavelength of 20 to 30 km (like the S^1 mode), with a great dissipation of energy (unexplainable for the S_1^1 mode).

Diurnal tide - north-south component

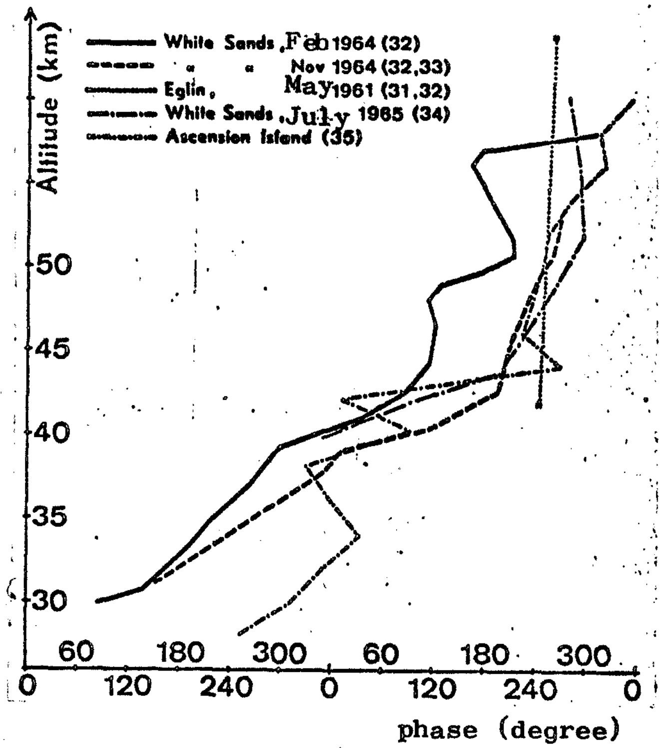


Figure 31. Variations of the phase of the diurnal tide with the altitude between 30 and 60 km: north-south component.

Comparison of results obtained at places with similar latitudes at different periods of the year. The winds are counted positively towards the north.

Diurnal tide - east-west component

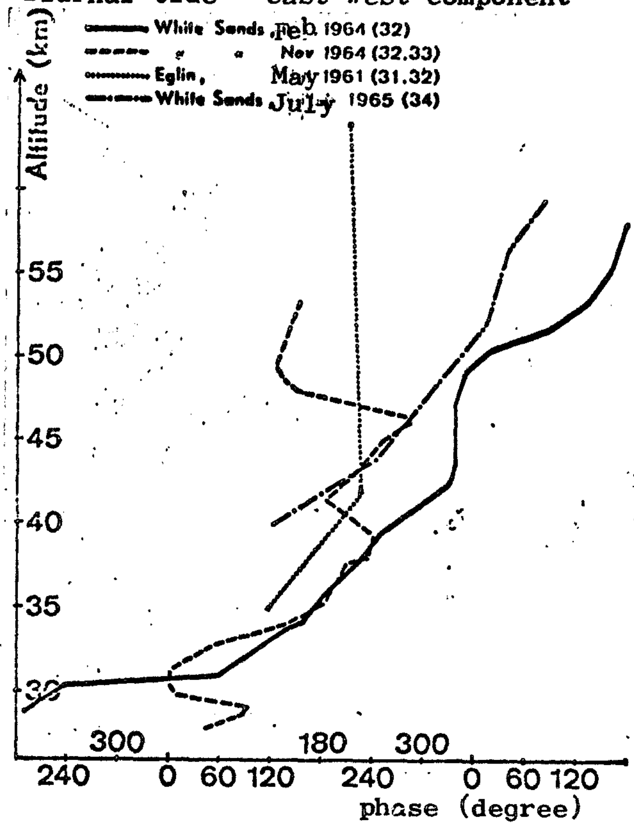


Figure 32. Variations of the phase of the diurnal tide with the altitude between 30 and 60 km: east-west component.

The wind is counted positively towards the east.

V. Small-scale Winds: Gravity Waves

The first experiments allowing study of small-scale winds used the reflection of the waves at two neighboring points of the same meteor trail [Greenhow and Neufelt, 1959 a and b; Greenhow, 1950 and 1952; Manning, 1959; Kent, 1960; Revah and Spizzichino, 1963 and 1964; Muller, 1968]. Beginning from a statistical study of the difference of winds at two neighboring points, there was shown the existence of components of the wind whose period is on the order of several hours and whose vertical self-correlation radius is approximately 6 km.

The statistical description of small-scale winds produced in this way did not allow choice of a solution from among several possible explanations: Greenhow and Neufeld believed they recognized a turbulent motion, in spite of properties rather uncommon for turbulence: considerable anisotropy, absence of correlation with the vertical gradient of the wind [Greenhow and Neufeld, 1969 a], systematic existence of heavy shearing zones [Revah, Spizzichino, 1963 and 1964]. Hines has shown that these small-scale winds are better explained by the propagation of gravity waves. In support of this argument, Hines refers to results of optical observations of meteors [Hines, 1960] and artificial clouds [Hines, 1964], showing quasi-periodic variations of the winds as a function of altitude, with wavelengths on the order of about twenty kilometers. Unfortunately, this type of experimentation hardly allows following the temporal variations of the wind and nothing allows affirmation that the quasi-periodic variations observed do not belong to the diurnal tide which, as we have seen, has a wavelength with the same order of magnitude. /21

The Garchy radar, which supplies a complete description of the variations of the zonal wind, allows a more exact study of the small-scale zonal winds. We have seen (Figures 2 and 3) that the spectrum of the winds measured at Garchy causes the appearance of components with a period included between 2 and 10 hours. A detailed study of these components has formed the subject of previous publications. We shall confine ourselves to a summary of the chief results:

1. The energy spectra of the wind produced for each observation run show,

for periods of from 2 to 10 hours, a series of significant maxima (Figures 33 and 34). Each one of these maxima represents one oscillation whose phase increases linearly with altitude (Figure 35). These oscillations therefore are propagated like waves. Their phase velocity v_{Φ}, which can vary from 1 to 20 km/hr, is almost always directed downwards. It has been shown [Spizzichino and Revah, 1968; Revah, 1969] that, under these conditions, it is possible to assimilate these waves to gravity waves whose energy is propagated upwards.

For each wave observed, it is possible to calculate the vertical wavelength $\lambda = v_{\Phi}\tau$ (τ is the period). We shall discuss this point more in detail later on.

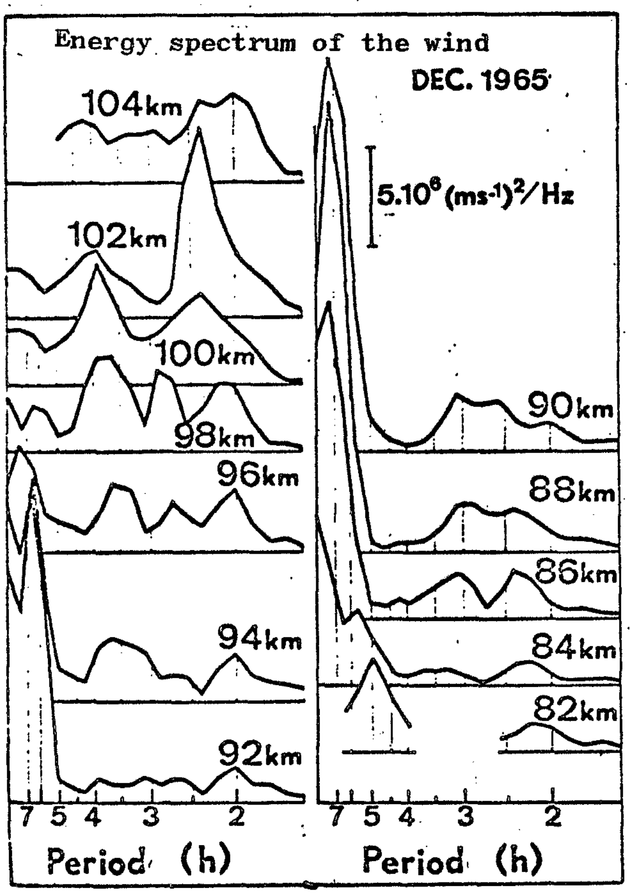


Figure 33. Spectrum of the small-scale winds. Garchy, 14 - 16 December, 1965.

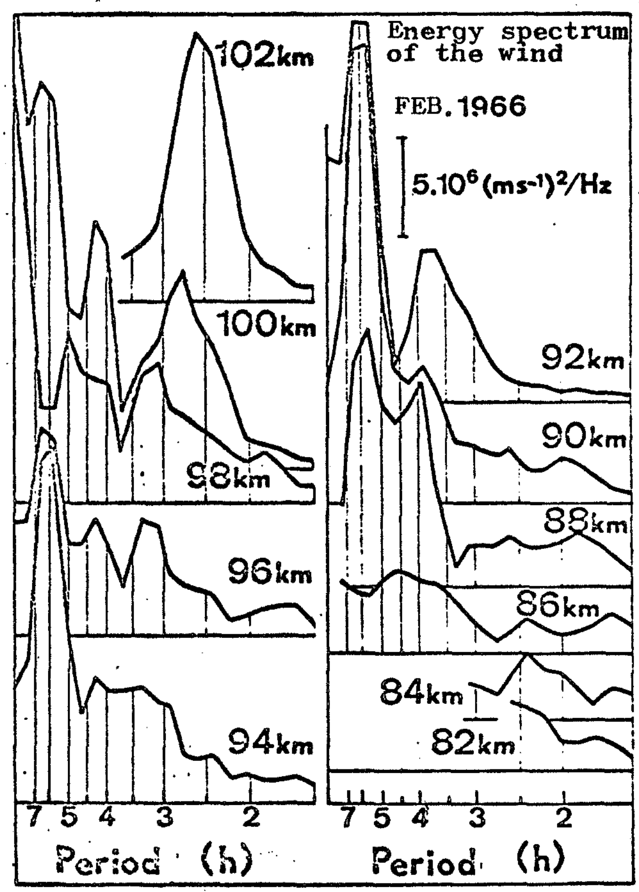
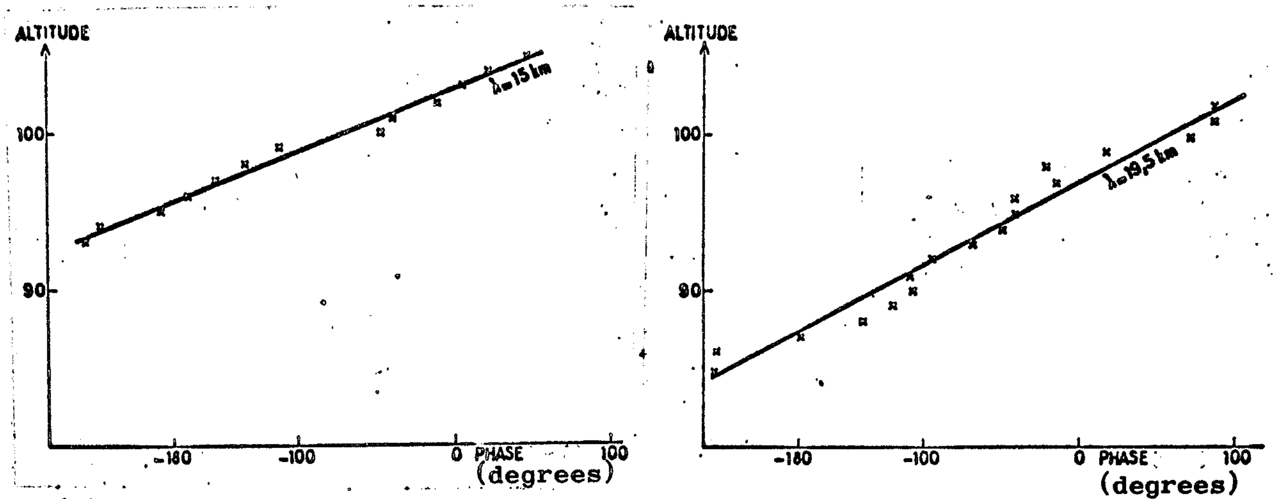


Figure 34. Spectrum of the small-scale winds. Garchy, 22 - 24 February, 1966.

2. The amplitude of each one of these sinusoidal components varies as a function of altitude by alternately passing through maxima and minima, with the distance between one consecutive maximum and minimum being in the vicinity of $\lambda/4$. This shows that, with each wave observed, there is associated a wave with smaller amplitude which is propagated in the reverse direction like a reflected wave. /22



(a) December, 1965
3 hr. 30 min. period.

(b) February, 1966
6 hr. period.

Figure 35. Examples of variations of the phase as a function of altitude for various maxima of the spectrum of small-scale winds.

(a) 22 - 24 February 1965, component of 6 hour period.
(b) 14 - 16 December 1966, component of 3 hour, 30 minute period.

3. Once the two waves which are propagated in the reverse direction are separated, it may be ascertained that the one which is propagated upwards (i.e. whose v_Φ is directed downwards) shows an unexplainable anomaly, appearing for practically all components with periods less than 4 hours. Their energy density increases with altitude.

Now, theory tells us that gravity waves such as those observed at Garchy should lose very little energy owing to viscosity. Their energy per unit of volume should remain constant and their amplitude then becomes proportional to exp (z/2H). This result is similar to the one which we used (para. 4) to show that the diurnal tide loses energy. However, whenever the amplitude of diurnal tide increases more slowly than exp (z/2H), the amplitude of these gravity waves increases more swiftly than this quantity, showing that their energy increases with altitude.

4. Although the spectra of winds produced for each run show, as we have seen, discrete maxima, the mean spectrum calculated for the aggregate of runs has the appearance of a continuous spectrum (Figure 36). It shows no significant maximum (no ter- or quater-diurnal tide) and decreases practically on a uniform basis when frequency f increases.

Mean spectrum of small-scale winds - Garchy (1965-1966).

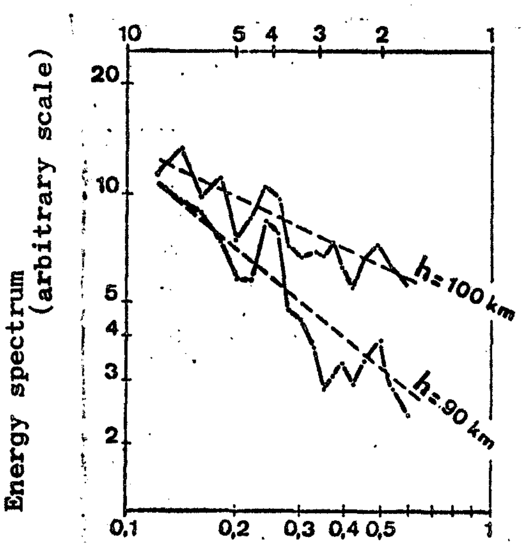


Figure 36. Mean spectrum of winds at 90 and 100 km calculated using the aggregate of the measurement runs of the Garchy radar.

When frequency f increases, the spectral density decreases as $f^{-0.82}$ at 90 km and as $f^{-0.47}$ at 100 km.

The decrease of the mean spectrum S(f) can be depicted quite well by a law in the form:

$$S(f) \propto f^{-\alpha}$$

in which, as can be seen in Figure 36:

α = 0.82 at 90 km altitude

0.47 at 100 km altitude.

In general, the decrease of S(f) is quicker at the lower altitudes. This furthermore appears quite distinctly on the spectra of most of the runs (Figure 37).

Comment - It is shown that the analytic method used acts like a low-pass filter whose cutoff frequency corresponds to a period of 1.5 hour. We have taken account of the response curve of this filter so as to correct the mean spectra provided by Figure 36 (this correction was not taken into consideration in [Revah, 1969], leading to higher values of α). However, in the case of periods less than 1.5 hour, the correction to be made would be too large for it to be able to produce significant results. It can therefore be stated that, at the present stage, the Garchy radar does not recognize components with a period less than 1.5 hour. /23

Energy spectrum of the E-W wind.

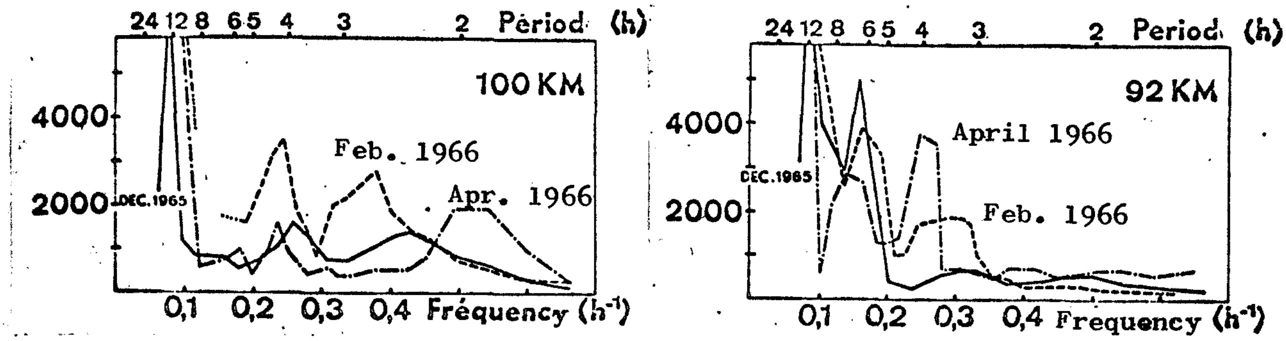


Figure 37. Comparison between the spectra of winds observed at Garchy in December 1965, February and April 1966, at 92 and 100 km in altitude.

These examples show that, at high altitudes, the spectrum of the winds is extended further towards the high frequencies.

Vertical wavelength of gravity waves.

We shall supplement the report of these properties - whose detailed description will be found by the reader in [Revah, 1969], by the results of a more recent study on the wavelengths of observed oscillations.

It is now clear that the two-dimensional Fourier analytic method, already applied by us to the diurnal tide, can be advantageously used for the study of gravity waves.

Indeed, whenever the wind results from the superposition of several wavy components, it may be shown that the two-dimensional spectrum S(f, k) should reveal as many distinct maxima. An error calculation shows that the separation of the wavy components produced in this way is better than the one supplied by a spectrum with only one dimension. This means that the two-dimensional spectrum should cause the appearance of a greater number of components in a significant manner. This is indeed confirmed by experience. The experimentally produced two-dimensional spectra always have several distinct maxima (one example is provided by Figure 38). The more numerous gravity waves revealed in this way are better adapted to a statistical study.

Figure 39 recapitulates the characteristics of all wavy components observed by the Garchy radar being propagated downward. Each one of them is depicted by a circle whose radius increases with the amplitude of this com-

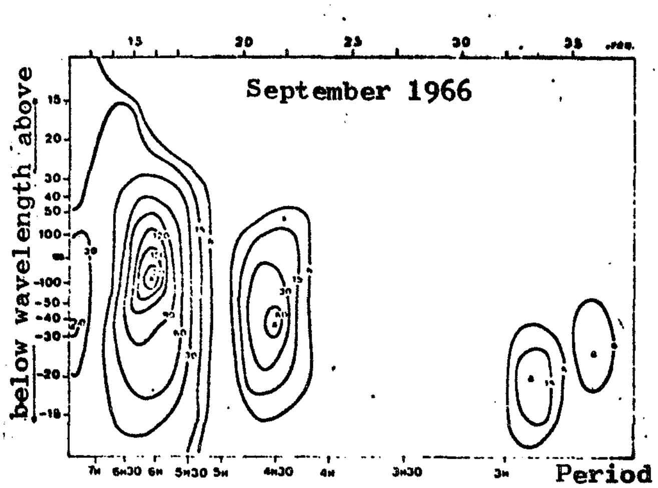


Figure 38. Two-dimensional spectrum S (f, k) of the small-scale winds observed at Garchy from 13-15 September 1966.

The curves S(f, k) = constant are plotted on a diagram in which frequency f appears as the abscissa and the wave number k as the ordinate. The spectrum S(f, k) has several significant maxima. Each one of them therefore represents a wave, with a given frequency and wavelength. The values of S are plotted with an arbitrary scale.

ponent. Its period is plotted as the abscissa and its vertical wavelength as the ordinate. The reader will recognize the circles corresponding to the semidiurnal tide (period: 12 hours), to the diurnal tide (period > 12 hours), and to the gravity waves (period < 12 hours). This figure shows that:

1. Most gravity waves observed have a wavelength included between 15 and 30 km.

2. We have seen in paragraph 4.B - and confirmed by Figure 39 - that, provided an exception is made of some components with a great wavelength and period exactly equal to 24 hours (which could depict a locally energized di- /24
urnal tide), the diurnal tide most often appears as a wave whose wavelength varies around 20 km. It can therefore be seen that the tide and gravity waves have wavelengths with the same order of magnitude.

Let us note that these results find their confirmation in most of the analysis of wind profiles produced beginning from luminescent clouds. Quasi-sinusoidal fluctuations of the wind appear as a function of altitude, with wavelengths of 10 to 30 km which researchers attribute sometimes to gravity waves [Hines, 1964; Kochanski, 1964 and 1966], sometimes to the diurnal tide [Hines, 1966], and sometimes to the semidiurnal tide [Rosenberg and Justus, 1966].

These results are in no way incompatible with the theory of gravity waves. Let us recall that this theory only allows predicting between what limits ought to include the period and wavelength of the waves which can arrive at each altitude without being either reflected or absorbed [Hines, 1960; Hines and Pitteway, 1965; Pitteway and Hines, 1963]. Within these limits, the theory neither allows specifying the exact form of the spectrum nor the effectively observed values of the wavelength, the former being a function of the manner in which these waves are energized.

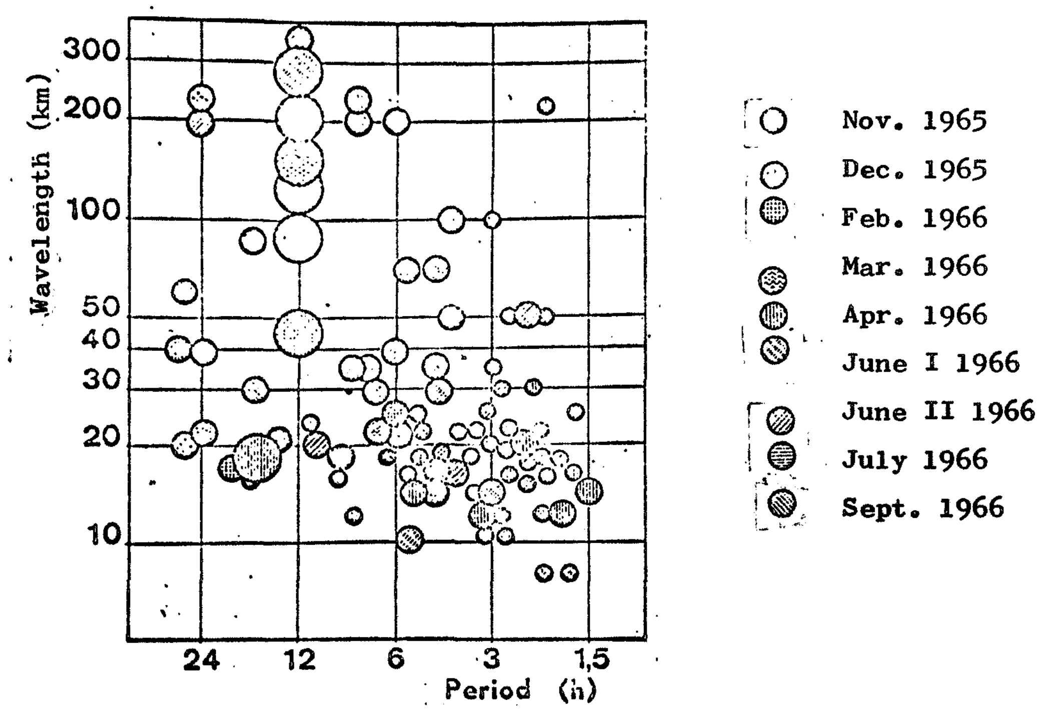


Figure 39. Frequency and wavelength of the different components of the wind observed at Garchy, from November 1965 to September 1966.

It has been noted that the semidiurnal tide is generally assimilatible to a wave with given vertical wavelength (paragraph 3), whereas the diurnal tide (paragraph 4B) and small-scale winds (paragraph 5) may be reduced to a superposition of such waves. This figure recapitulates the aggregate of the waves observed at Garchy during the nine observation runs. Each one of them is depicted by a circle whose diameter is a function of its amplitude and whose abscissa and ordinate depict the frequency and vertical wave number.

It may be seen that the circles depicting the semidiurnal tide, with great wavelength, form a rather closely grouped family whereas there is no clear discontinuity among those depicting the diurnal tide and those depicting the gravity waves.

Figure 40 shows that the characteristics of the waves observed by the Garchy radar are included within the limits predicted by the theory. The latter is hence compatible with the properties listed above, but alone does not suffice to explain any of these properties.

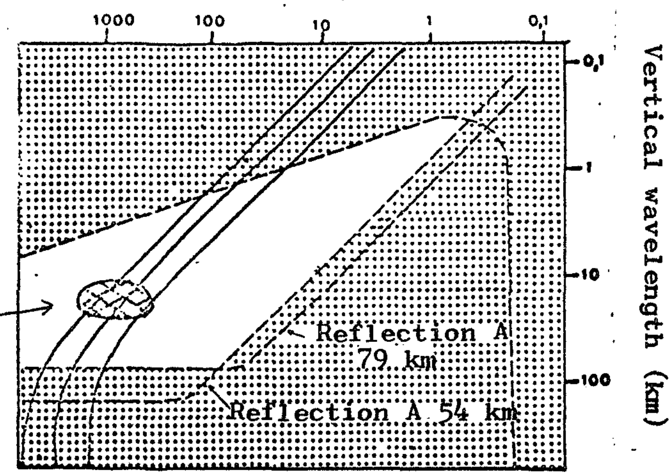


Figure 40. Characteristics of the gravity waves observed at Garchy: comparison with theory.

On this diagram in which the lengths of the horizontal and vertical wave are plotted respectively as abscissas and ordinates and in which the curves with constant curve are plotted, there has been depicted:

on one hand, the field occupied by the gravity waves observed at Garchy,

on the other hand, the "allowed field," in which, according to Hines [1960], the waves can be propagated up to 90 km of altitude without being either reflected or damped by viscosity.

The second field is much more extensive than the first one: the characteristics of observed gravity waves are compatible with the theory, but the latter does not suffice to explain them.

VI. Intuitive Explanation of Some Properties of Winds

The preceding study shows that the conventional theory of propagation of atmospheric waves leaves unexplained several properties of tides and gravity waves. We shall see, in the following discussions, that most of these properties /25 can be explained by non-linear interactions between the different components of the wind. Before starting the theoretical study of these interactions, we shall try to give them an intuitive description.

Let us first of all examine the properties of the diurnal tide. The non-uniform variations of its phase and amplitude above 80 km cannot be explained by a non-uniform energization of this tide. Indeed, the diurnal variations of the solar heating are reproduced identically each day and would be in no position to account for variations in phase reaching 180° observed in the case of the diurnal tide at high altitude. We know, furthermore, that at altitudes of 30 to 60 km, closer to the region in which the diurnal oscillation is energized, its phase is rather stable (paragraph 4c). It is therefore necessary to explain the non-uniform variations of the diurnal tide by phenomena becoming a factor during its propagation, between the level at which the tide is energized and the altitude interval 80 - 110 km in which it is observed.

We should therefore understand why the characteristics of the diurnal tide undergo non-uniform variations during its propagation whereas those of the semi-diurnal tide remain stable. Figure 41 shows an intuitive explanation of this based on some simple examples.

Figure 41a shows these two tides being propagated in an undisturbed atmosphere. The variations of the wind are depicted as a function of time and altitude (positive wind in the shaded zones, negative in the unshaded zones). In order to take into account, diagrammatically, the difference in order of magnitude between the wavelengths of these two tides, they have been depicted as being propagated with a constant wavelength, 20 km for the diurnal tide and 100 km for the semidiurnal tide.

Figure 41b depicts the same tides in an atmosphere disturbed by the presence of a constant vertical wind. The aggregate vertical shift of the atmosphere has the effect of modifying the frequency of oscillations observed at a specified altitude. Although, in this figure, there was awarded to the vertical wind a

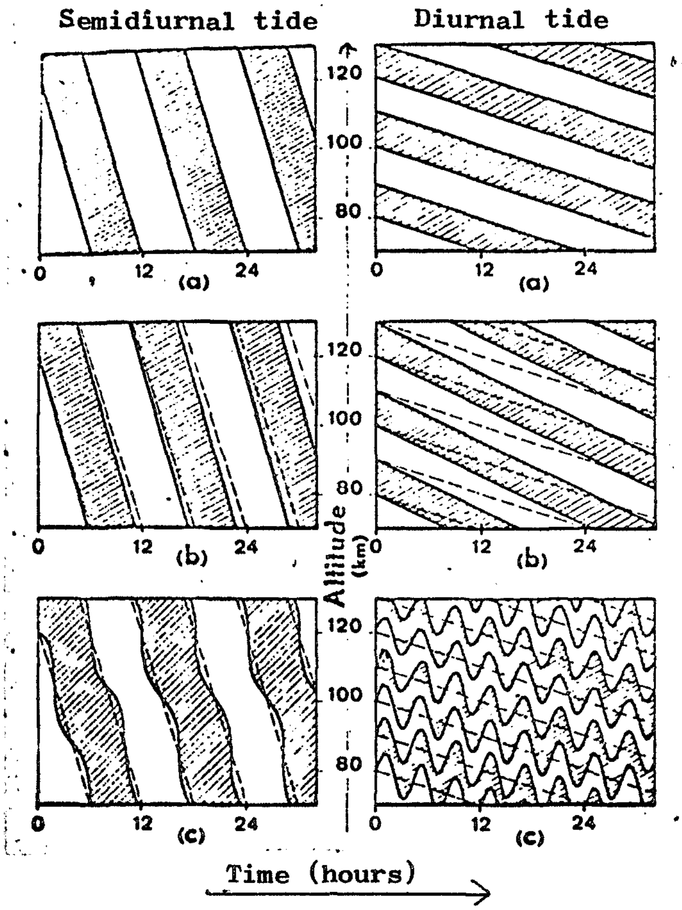


Figure 41. Diagramatic representation of a semidiurnal tide with a 100 km wavelength and a diurnal tide with a 20 km wavelength:

(a) in an undisturbed atmosphere,

(b) in an atmosphere actuated by a continuous vertical motion, at a velocity of 0.1 ms^{-1},

(c) in an atmosphere actuated by a vertical oscillating motion (amplitude: 2 m/s, period: 4 hours).

In case (b), it is seen that the period of the diurnal tide is greatly modified (it becomes equal at 17 hours). In case (c), the tide has yielded a part of its energy to a horizontal oscillating motion. In both cases, the semidiurnal tide has hardly been disturbed.

very low value (0.1 m/s), the period of the diurnal tide thus observed is greatly modified (on the order of 17 hours), without its vertical wavelength being changed. Thus, there is a simple explanation for the oscillations with periods in the vicinity of 24 hours and a wavelength of 20 to 30 km observed at Garchy. These probably depict a diurnal tide disturbed by a prevailing vertical wind. The presence of a mean vertical wind of 0.1 m/s is in no way unreasonable since it is known that the instantaneous vertical wind can reach 2 to 10 m/s [Edwards et al., 1963]. No experimental data is presently available on the mean value of this vertical wind. The observations of the Garchy radar therefore suggest, indirectly, an order of magnitude of 0.1 m/s which would take into account values of the period of observed waves. This order of magnitude cannot be exceeded in all cases, or else the diurnal oscillation, whose period observed from the ground could assume any value whatever, could never have been detected.

On the other hand, it can be seen from Figure 41b that the semidiurnal tide is, on the contrary, only slightly disturbed. Its period has hardly varied

(11 hours 30 minutes instead of 12 hours), the corresponding phase shift from one period to the other, hardly detectable (approximately 15°), is on the order of magnitude of the phase fluctuation observed for the semidiurnal tide (Figure 5). This appears to confirm the order of magnitude of 0.1 m/s, at least as an upper limit of the mean vertical wind.

What we have just stated for a constant vertical wind can also be applied /26 to other vertical motions. In Figure 41c, it was assumed that the aggregate of the atmosphere is actuated by a vertical oscillating motion. This would be the case if the atmosphere were disturbed by a gravity wave with a very long vertical wavelength (its amplitude was assumed to be 2 m/s^{-1}, which is reasonable [Edwards et al., 1963], and a 4 hour period). The figure shows that the horizontal wind measured at a specified atltitude then has periodic variations whose:

period is very close to the one for the vertical oscillating motion;

wavelength is the same as the one for the tide (this law is only approximate if the vertical oscillation has a large but not infinite wavelength).

It will be convenient, in the following, to term "primary oscillation" the vertical oscillation affecting the atmosphere and "secondary oscillation" the horizontal fluctuation of the wind measured at a specified altitude. The secondary oscillation, arising from interaction between the primary oscillation and the tide, has an amplitude proportional to that of the tide. Provided that the latter is strong enough, the amplitude of the secondary wave can exceed any value given in advance, and more particularly be greater than that of the primary oscillation. The atmosphere behaves like an amplifier whose energy is supplied by the tides, i.e., in the last analysis, by solar heating.

It can be ascertained from Figure 41c (and it can be easily confirmed) that, in the case of a same primary oscillation, the diurnal tide gives rise to secondary oscillations which are much stronger than the semidiurnal tide. We shall see in Part IV that every gravity wave being propagated in a region of strong diurnal tide (i.e., at the lower latitudes) can give rise in this way to a secondary wave which is then propagated beyond the region from which it arose. It is thus possible to explain the presence at 100 km of altitude of waves with various periods having wavelengths of the same order as for the diurnal tide as we have seen in paragraph 5. This can also explain how the diurnal tide is propagated with loss of energy (paragraph 4).

In this way, a very simple intuitive display has shown us that several properties of the diurnal tide and gravity waves which appeared inexplicable have, on the contrary, an obvious explanation if allowance is made for the existence of interactions between various components of the wind (between the diurnal tide and a vertical wind, between the diurnal tide and gravity waves). In the following chapters, we are going to try, beginning from a more detailed study of these interactions, to explain all the properties of the gravity waves observed at Garchy.

Manuscript received 5 May 1969.

Annex

Dates of wind observations

16-17 November 1965.	8-10 June 1966 (designated June I in text).
14-16 December 1965.	21-24 June 1966 (designated June II in text).
22-24 February 1966.	19-22 July 1966.
29 March - 1 April 1966.	13-15 September 1966.
27-28 April 1966.	

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